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RM E52B14



APR 28 1952

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RESEARCH MEMORANDUM

RELATIONS BETWEEN FUEL PROPERTIES AND

COMBUSTION CARBON DEPOSITION

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Cleveland, Ohio~~CLASSIFICATION CHANGED~~To Confidential
NACA rel. for #1695 - Exec. Order 78501By authority of J. W. Crowley Date 7/2/9/53
CLASSIFIED DOCUMENT 7/2/17/53

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

RELATIONS BETWEEN FUEL PROPERTIES AND COMBUSTION

CARBON DEPOSITION

By Edmund R. Jonash, Jerrold D. Wear,
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SUMMARY

Methods for predicting the carbon-forming propensity of turbojet-engine fuels from results of simple laboratory tests of the fuels are discussed. The accuracy and reliability of the methods, and the simplicity of the laboratory tests required, are considered with a view toward the application of such methods for the control of jet fuel quality. The prediction of carbon deposition from fuel characteristics including aromatic content, hydrogen-carbon ratio, distillation temperatures, gravity, and aniline point, and from several empirical laboratory carbon-deposition tests is illustrated with data from several turbojet-combustor test units and a large number of widely different fuels.

Of the methods considered, the prediction of carbon deposition from a function of hydrogen-carbon ratio and volumetric average boiling temperature (NACA K factor) was one of the most accurate. Results of tests of a large number of fuels in a J33 tubular combustor indicated an average deviation of the carbon-deposition data from the predicted correlation of 16 percent, which was comparable to the deviation of 10 to 20 percent expected with data for any one fuel. Since conventional methods for determining the hydrogen-carbon ratio of a fuel may be more complex than would be desirable for routine fuel quality control, empirical correlation methods for estimating this factor were compared. The prediction of carbon deposition from such estimated values of hydrogen-carbon ratio are subject to greater inaccuracies than are encountered in the prediction from determined values of hydrogen-carbon ratio.

Precision comparable to the NACA K factor method was obtained in the prediction of carbon deposition from smoking tendency of the fuel by a laboratory lamp. This method, although requiring one of the least complex test techniques, was considered to require additional data to establish the reproducibility of the test method among laboratories.

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Based on limited data, previously obtained on full-scale turbojet engines, the numerical limits of the fuel quality control methods were established at an NACA K factor of 310 or a smoking tendency of 13.

INTRODUCTION

A critical problem encountered in the operation of turbojet engines with current, wide-boiling-range hydrocarbon fuels is combustion-chamber carbon deposition. The formation of carbon on fuel injectors causes alterations in fuel-spray pattern with possible effects on combustor performance; similar effects on performance can result from the deposition of carbon on primary air-entry ports. Altitude starting may be impaired by the deposition of carbon on spark plug electrodes, which either shorts the electrodes completely or causes the spark to occur at positions other than the intended gap (reference 1). Finally, the deposition of carbon on high-temperature areas of combustor liners promotes liner cracking and warping from excessive temperature gradients and variations in thermal expansion rates.

For combustor operation at any required conditions, carbon deposition is dependent upon two factors: combustor design (including fuel injection and ignition) and choice of fuel. While carbon deposition may be reduced considerably in future combustor designs, the combustor modifications necessary in current designs may result in a deterioration of other performance characteristics. With respect to the fuel properties, however, changes which alleviate the carbon-deposition problem also promote, in general, increased over-all performance. Therefore, if limits in fuel characteristics can be selected which will adequately control carbon deposition without an excessive compromise in fuel availability, the inclusion of such limits in turbojet-engine-fuel specifications would be desirable.

A substantial quantity of data has been obtained at the NACA Lewis laboratory, and at a number of other laboratories, describing the effects of various fuel properties on carbon deposition in small-scale and full-scale single-tube combustors and in full-scale engines. Several correlations developed from these investigations, together with a number of relatively simple laboratory test procedures, have been suggested as possible methods for estimating the carbon-deposition propensity of fuels. The purposes of the discussion presented herein are (1) to describe and compare the prediction of carbon deposition by means of these fuel-property correlations and empirical laboratory tests, and (2) to consider their use in fuel procurement specifications for the control of turbojet-engine carbon deposition.

The fuel characteristics which are considered as representing chemical and physical properties of the fuel include the hydrogen-carbon ratio, aromatic content, aniline point, A.S.T.M. distillation temperatures,

and gravity. The empirical laboratory tests representing fuel combustion properties include smoking tendency (reference 2), flame plate (reference 3), and "pot" burner (unpublished). No detailed consideration is given small-scale combustor tests, since such tests would not represent simple routine laboratory control methods. In order to compare the applicability of the suggested carbon-deposition control methods to broader ranges of combustor types, combustor operating conditions, and fuel properties, carbon-deposition data obtained at a number of laboratories, in addition to the NACA Lewis laboratory, are included.

Comparisons of the relative merit of these control methods will include consideration of not only the accuracy of carbon-deposition prediction, but also the complexity of the required laboratory test. A description of the equipment, personnel, and time requirements for the various laboratory tests required is presented herein.

FUELS, APPARATUS, AND PROCEDURE

Fuels. - The chemical and physical properties of the fuels investigated at the NACA laboratory are presented in table I. Pertinent properties of the majority of fuels investigated at other laboratories are presented in table II. In order to avoid errors in carbon-deposition data arising from lead deposition, leaded fuels are not included herein.

Apparatus. - Carbon-deposition data were obtained at the NACA laboratory in a single-tube J33 and a $10\frac{3}{8}$ -inch-diameter annular combustor. These test units were installed in the laboratory supply and exhaust facilities as shown schematically in figure 1. Complete descriptions of NACA test apparatus and instrumentation are presented in reference 4 (J33 combustor) and reference 5 (annular combustor), and of those used by other laboratories in references noted in table II.

A description of laboratory fuel test methods considered is presented in appendix A.

Procedure. - The J33 and annular combustor investigations (NACA) were conducted at the following combustor test conditions:

Condition	Combustor	
	J33	Annular
Inlet-air pressure, in. Hg absolute	53.9	40.0
Inlet-air temperature, °F	271	100
Air flow rate, lb/sec	2.87	2.50
Fuel-air ratio	.0120-.0123	.0175
Test duration, hr	4	2

The quantity of carbon deposited was determined by weighing the combustor inner liner before and after each test run. The liner was cleaned prior to each run with mechanical rotating wire brushes. The test conditions and procedures used in the investigations of other laboratories are presented in the references noted in table II.

RESULTS AND DISCUSSION

In the following discussion, primary consideration will be given to carbon-deposition control methods which involve direct measurements of the physical and chemical characteristics of the fuel, since these characteristics should fundamentally determine the carbon-forming propensity of the fuel. Because of the simplicity of the laboratory techniques involved, consideration will next be given to those control methods which involve only indirect measures of the physical and chemical characteristics. Finally, the several empirical laboratory tests which simulate, to a certain extent, actual combustor carbon-forming conditions will be considered. A detailed discussion of the reproducibility and the laboratory equipment and personnel requirements for the various fuel quality control tests is presented in appendix A.

Fuel Composition and Volatility

Aromatic content and A.S.T.M. distillation temperature. - Results of many early combustor investigations indicated, qualitatively, that an aromatic-type fuel produces larger quantities of carbon than do other types of fuel. In addition, it was observed that a reduction in fuel volatility increases carbon deposition. These two fuel properties were combined (reference 6) to correlate carbon deposition with the function percent aromatics plus 0.10 times the 80-percent A.S.T.M. distillation temperature. Although satisfactory correlations were obtained by one laboratory (reference 6), the same function applied to data obtained in the two combustor test units at the NACA laboratory resulted in a relatively poor correlation (fig. 2). A substitution of the 90-percent A.S.T.M. distillation temperature for the 80-percent temperature, according greater weight to the even less volatile fuel fractions, may in some cases improve this correlation.

From very limited data, correlations of carbon deposition with functions of the high-boiling (greater than 400° F) aromatic content and with functions of the naphthalene content have been suggested. A serious objection to any of these correlations as possible control methods is the difficulty and inaccuracy of the direct determination of fuel composition (appendix A).

Hydrogen-carbon ratio and volumetric average boiling temperature. - Since it appears from the results cited previously that increased aromatic content and decreased volatility of the hydrocarbon fuel will

increase carbon deposition, a correlation including a direct measure of these fuel characteristics was developed. Thus a function of the hydrogen-carbon ratio and the volumetric average boiling temperature, the K factor (appendix A), was used to predict the carbon-deposition characteristics of 19 fuels in the annular combustor (reference 5) and was later applied to limited single-tube-combustor data (references 4 and 7). The K factor correlations obtained are presented in figure 3. The correlation shown in figure 3(a) includes data of references 4 and 7 and additional data obtained over a considerable period of time in two similar J33 combustor test setups operated at similar conditions. Figure 3(b) presents, for comparison purposes, the correlation of data from reference 5 (annular combustor). The application of this correlation to data obtained from several other laboratories (data which include hydrogen-carbon-ratio analyses of the fuels) is shown in figure 4. Data obtained in J31 combustors are presented in figures 4(a) to 4(d); in general, only marginal correlations were obtained. The J42 combustor data (fig. 4(e)) indicate very poor correlation, and the limited J33 combustor data (fig. 4(f)), good correlation. In these correlations, also, a difficulty is encountered in the determination of one fuel factor, the hydrogen-carbon ratio. The various methods which may be used to obtain this factor are discussed in appendix A.

Related Fuel Properties

API gravity and volumetric average boiling temperature. - Since for most hydrocarbon fuels a relation exists between the hydrogen-carbon ratio and a function of the boiling temperatures and gravity (reference 8), it would be expected that the hydrogen-carbon ratio may be eliminated from the carbon-deposition correlation. The resulting correlation involving only gravity and the volumetric average boiling temperature is shown in figure 5 for data obtained at the NACA laboratory. The derivation of this correlation is described in appendix A. The small increase in data scatter over that observed in figure 3 reflects the additional error introduced in the estimation of hydrogen-carbon ratios of the fuels.

API gravity. - The gravity of typical mixed hydrocarbon fuels will indirectly reflect both composition and volatility characteristics. For this reason, carbon deposition would be expected to correlate with gravity. This correlation for NACA J33 combustor data is shown in figure 6(a). Because of the simplicity of the laboratory technique required for this control method, its application to data obtained by other laboratories and other combustors is presented in figure 6(b) to 6(i). It is noted that reasonable correlations resulted for data obtained in the J33 tubular combustors (figs. 6(a) to 6(e)) and in the annular combustor (fig. 6(h)); poor correlations resulted for data obtained in the J31 combustors (figs. 6(f), 6(g), and 6(i)).

API gravity, aniline point, and volumetric average boiling temperature. - An empirical correlation of the gravity, aniline point, and volumetric average boiling temperature with the hydrogen-carbon ratio is presented in reference 9. The accuracy of hydrogen-carbon ratio estimates by this method is discussed in appendix A. The correlation of carbon deposition with hydrogen-carbon ratio and volumetric average boiling temperature (fig. 3), using hydrogen-carbon ratios estimated by the method of reference 9, is shown in figure 7 (NACA J33 combustor data only). The deviations from the correlation line are greater than those observed in the original correlation (fig. 3), again indicating the additional error introduced in the estimation of hydrogen-carbon ratio by this method.

Aniline-gravity constant. - The relations between fuel volatility and gravity, and between hydrogen-carbon ratio and aniline point, suggest the possibility of correlating carbon deposition with aniline-gravity constant (appendix A). This correlation for data obtained at the NACA and other laboratories is presented in figure 8. Again, reasonable correlations were indicated with data obtained in the J33 tubular combustors (figs. 8(a) to 8(c)) and poor correlations were obtained with data obtained in the J31 combustors (figs. 8(d) and 8(e)).

Empirical Laboratory Tests

Smoking tendency. - The correlation of the smoking tendency of fuels with carbon deposition is presented in figure 9 for data obtained at the NACA and other laboratories. The smoking tendency of a fuel is represented by $320/h$, where h is equal to the maximum height of a smoke-free flame (appendix A). The correlations obtained with J33 combustor data (figs. 9(a) and 9(b)) were significantly better than those obtained with J31 data (fig. 9(c)) and with annular combustor data (fig. 9(d)). Some improvement in the annular combustor correlation was obtained by including a function of the volumetric average boiling temperature (reference 2), as shown in figure 10(a). Application of this combined factor to the J33 data of figure 9(a), however, somewhat reduced the degree of correlation, as indicated in figure 10(b). These results would imply that the empirical function of smoking tendency and volumetric average boiling temperature may not be generally applicable to different combustors or combustor operating conditions.

Pot burner. - Very limited data have been obtained on a pot-type burner suggested as a possible carbon-deposition fuel control test. For four fuels distributed to various laboratories by the Coordinating Research Council (CRC), the results of the one laboratory conducting pot-burner tests (unpublished data from the Texas Company) indicate marginal agreement with NACA J33 carbon-deposition data, as shown in figure 11.

Flame plate. - Limited data are available for this suggested carbon-deposition rating test. A comparison of flame-plate data (unpublished data from the California Research Corporation) and NACA J33 combustor data for the same CRC fuels noted previously indicates relatively poor agreement (fig. 12(a)). A comparison of flame-plate data with carbon-deposition data from another full-scale tubular combustor (reference 10 and unpublished data from California Research Corporation) shown in figure 12(b) indicates a fair agreement of data.

Small-scale burners. - No detailed consideration will be given to the use of small-scale (2-in. diameter) burners as a fuel quality control technique. Carbon-deposition data obtained in these units have, in most cases, compared favorably with data (unpublished) obtained in single-tube, full-scale combustors.

Comparison of Methods of Predicting Carbon-Deposition

Characteristics of Fuels

Before the relative merits of the fuel quality control methods are compared, the accuracy of carbon-deposition data used in deriving the methods should be examined. Results of a recent cooperative carbon-deposition program sponsored by the CRC allow an estimate to be made of the expected reproducibility of carbon-deposition data. For each of a large number of laboratory test units, in which more than one test run was conducted on each fuel, the following average and maximum deviations of the data were determined:

Laboratory test unit	Average deviation (percent)	Maximum deviation (percent)
A (small-scale combustor)	26	103
B (small-scale combustor)	54	200
C (small-scale combustor)	15	44
D (small-scale combustor)	26	150
E (small-scale combustor)	39	134
F (small-scale combustor)	15	48
G (small-scale combustor)	13	39
H (small-scale combustor)	15	29
I (full-scale combustor)	8	35
J (full-scale combustor)	23	62
K (pot burner)	12	27
L (flame plate)	42	83
NACA (full-scale combustor)	4	14

It is apparent that average deviations in carbon-deposition data from 10 to 20 percent can be normally expected; individual deviations as high as 100 to 200 percent may occur. Thus, any carbon-deposition correlation technique must be established from test data which include duplicate test runs on each fuel. Similarly, correlations applied to data representing few, if any, duplicate runs may exhibit large inherent deviations.

The comparison of the relative merits of the various fuel quality control methods will include consideration of the accuracy, or reliability, of the control and of the complexity of the experimental laboratory techniques required. The accuracy of each control method may be judged from comparison of the average and the maximum deviations of the carbon-deposition data from the predicted correlation curve. Sufficiently complete chemical analyses were available only for the fuels in the J33 combustor at the NACA laboratory to compare all quality control methods with a single set of data. Also, these data indicated a reproducibility at least comparable to that obtained by any of the other laboratories. For these reasons the comparison is restricted to this particular investigation:

	Number of fuels included	Average deviation (percent)	Maximum deviation (percent)
Fuel composition and volatility			
Aromatic content-A.S.T M. 80-percent distillation temperature	20	40	177
Hydrogen-carbon ratio and volumetric average boiling temperature	20	16	85
Related fuel properties			
Gravity and volumetric average boiling temperature	20	23	118
Gravity	20	24	140
Hydrogen-carbon ratio (estimated from gravity, volumetric average boiling temperature, aniline point) and volu- metric average boiling temperature	14	33	150
Aniline-gravity constant	14	36	200
Empirical laboratory tests			
Smoking tendency	16	16	65
Smoking tendency and volumetric average boiling temperature	16	21	65
Pot burner	4	123	400
Flame plate	4	63	117

These deviations must be considered qualitative only, since variations in the fairing of correlation curves through data at very low values of carbon deposition abnormally affect the determined deviation.

The comparison presented indicates that a number of quality control methods will predict carbon-deposition characteristics of fuels in the J33 single combustor with an average deviation of less than 25 percent, a limit which may, on the basis of data reproducibility, be considered satisfactory. These quality control methods include: hydrogen-carbon ratio and volumetric average boiling temperature; gravity and volumetric average boiling temperature; gravity; smoking tendency; and smoking tendency and volumetric average boiling temperature.

Maximum deviations are also of interest since they reflect the possibility of unsatisfactory fuels being acceptable within specified control limits, and conversely, of rejection of otherwise satisfactory fuels. For the control methods resulting in less than 25-percent (average) deviation, the corresponding maximum deviations varied from 65 to 140 percent. These large deviations may result from (1) the use of poor analytical or carbon-deposition data, (2) relatively minor deviations occurring at very low (and therefore unimportant) values of predicted carbon deposition, or (3) the omission of some fuel factor or factors from the correlation. With respect to item (3), above, some consideration has been given to the effect of two fuel factors, gum and sulfur content, on carbon deposition. Various published and unpublished results of investigations (for example, references 11 to 14) of these two factors disagree considerably; however, for fuels within the present turbojet-engine fuel specifications, any effect appears to be a very minor one.

The lowest average deviations (approximately 16 percent) were obtained with the correlation of hydrogen-carbon ratio and volumetric average boiling temperature, and the correlation of smoking tendency. The first control method might be considered superior in that the carbon-forming propensity of the fuel is related to the more fundamental characteristics of the fuel. As noted previously, however, the determination of hydrogen-carbon ratio is difficult and time consuming, as a routine laboratory control test. Some simpler alternative methods for determining this factor are discussed in appendix A. It was shown that the use of some of these alternative methods (correlations of various fuel properties) results in substantially increased deviations.

A very satisfactory correlation was indicated for the smoking tendency of a fuel, a very simple laboratory technique being required. The application of this method has not been investigated extensively, and

the accuracy of reproducing results among different laboratories has not been determined. There are possibilities, however, that the problem of reproducibility among laboratories could be minimized through the use of a simple rating scale employing two reference fuels (appendix A).

The simplest of control methods considered include gravity and the aniline-gravity constant, both of which are presently required in fuel specifications. One objection to the use of gravity as a control method is the increasing effect of gravity on carbon deposition as the gravity ($^{\circ}$ API) of the fuel is decreased. Also, with both the gravity and the aniline-gravity constant correlations, excessive maximum deviations were observed.

The preceding comparisons included fuels which may not be considered for jet-engine use because of other specification limits or availability requirements. A more realistic indication of the accuracy to be expected with the correlation parameters may be obtained by considering only those fuels having volatility characteristics meeting the MIL-F-5624A specifications. Table III compares the Reid vapor pressure and A.S.T.M. distillation temperatures of the fuels of table I(a) with the MIL-F-5624A specifications. It is noted that 14 fuels meet either the grade JP-3 or the JP-4 volatility requirements. For these fuels only, the following average and maximum deviations were determined:

	Number of fuels included	Average deviation (percent)	Maximum deviation (percent)
Fuel composition and volatility			
Aromatic content-A.S.T.M. 80-percent distillation temperature	14	29	177
Hydrogen-carbon ratio and volumetric average boiling temperature	14	12	85
Related fuel properties			
Gravity and volumetric average boiling temperature	14	20	118
Gravity	14	16	25
Hydrogen-carbon ratio (estimated from gravity, volumetric average boiling temperature, aniline point) and volu- metric average boiling temperature	10	30	150
Aniline-gravity constant	10	36	200
Empirical laboratory tests			
Smoking tendency	10	16	65
Smoking tendency and volumetric average boiling temperature	10	17	50
Pot burner	2	22	24
Flame plate	2	30	39

It is noted that in most cases, the average deviations were reduced somewhat; the maximum deviations in some cases were reduced substantially. The lowest average deviations were obtained with the correlation of hydrogen-carbon ratio and volumetric average boiling temperature. Slightly greater deviations were obtained with correlations of gravity, smoking tendency, and smoking tendency-volumetric average boiling temperature.

For MIL-F-5624A grade JP-4 fuels only, the following average and maximum deviations were obtained:

	Number of fuels included	Average deviation (percent)	Maximum deviation (percent)
Fuel composition and volatility			
Aromatic content-A.S.T.M. 80-percent distillation temperature	5	62	177
Hydrogen-carbon ratio and volumetric average boiling temperature	5	12	21
Related fuel properties			
Gravity and volumetric average boiling temperature	5	9	16
Gravity	5	11	19
Hydrogen-carbon ratio (estimated from gravity, volumetric average boiling temperature, aniline point) and volu- metric average boiling temperature	4	19	35
Aniline-gravity constant	4	10	26
Empirical laboratory tests			
Smoking tendency	2	1	3
Smoking tendency and volumetric average boiling temperature	2	7	8

Unfortunately, the data available on JP-4 type fuels were so limited that no conclusions are justified. The information in the preceding table may indicate that as the ranges of fuel properties are reduced, improved correlations of some fuel properties with carbon deposition may be expected.

Application of Fuel Quality Control Methods

One assumption that must be made in considering the application of the fuel quality control methods is that fuels will rate similarly in single tube and in full-scale engines with respect to carbon deposition. Only very limited quantitative carbon-deposition data are available from full-scale turbojet-engine tests (references 7 and 15). Data comparing the carbon-deposition characteristics of satisfactory, marginal, and unsatisfactory fuels in both single combustors and full-scale engines are necessary in order to establish limiting values of any chosen fuel quality control method. The full-scale engines tested must, in addition, represent engines whose operations are most critically affected by carbon deposition.

At the present time the limited data available (reference 7) indicate that a fuel of minimum quality for satisfactory full-scale (J35) engine operation must have an NACA K factor (function of hydrogen-carbon ratio and volumetric average boiling temperature) of not more than 310. Additional data (appendix B) obtained from full-scale squadron operation indicate a somewhat higher maximum value of 325. A conversion of this quality control limit to another control limit can be accomplished by direct comparison with the quantity of carbon deposited in the J33 single combustor. Thus, for smoking tendency the limiting value of 320/h would be 13.0 or 16.5. Similar conversions can be made for gravity, aniline-gravity constant, or any other desired quality control method.

The carbon-deposition data obtained in the CRC program show the extent to which carbon deposition may vary among different combustion chambers (or circumferentially, in an annular chamber) of a full-scale engine. In addition, large variations in carbon deposition would be expected to be encountered in different flights because of the normal variations in operating conditions. It is necessary, then, to select the most conservative limit for fuel quality control that would be consistent with availability of adequate quantities of fuel meeting this limit.

CONCLUDING REMARKS

The problem of providing a quality control method for restricting the procurement of turbojet engine fuels to those allowing satisfactory operation, with respect to carbon deposition, has been considered. Such a control, incorporated in procurement specifications, should embody the following features:

(1) Prevent procurement of any fuel which may result in unsatisfactory operation, with respect to carbon deposition, in any production turbojet engine.

(2) Be sufficiently flexible to allow procurement of adequate supplies of the fuel in an emergency.

(3) Be sufficiently simple and reproducible to be treated as a routine quality control test.

2422 The fuel characteristics and related fuel properties which were considered to affect carbon deposition included aromatic content, hydrogen-carbon ratio, A.S.T.M. distillation temperatures, gravity, and aniline point. Empirical laboratory fuel tests which simulated carbon deposition included smoking tendency, flame plate, and pot burner.

Considering the accuracy of correlations derived from the above fuel factors, and the quality control requirements enumerated above, two control methods were chosen as being satisfactory. These methods were (1) function of hydrogen-carbon ratio and volumetric average boiling temperature, and (2) smoking tendency. The first method more nearly represents an ideal quality control function; however, it entails considerable difficulty in the determination of the hydrogen-carbon ratio. Alternative methods, some relatively untried, are suggested for obtaining this determination. At the present time the most suitable method appears to be the A.S.T.M. Lamp method (D1018-49T). The second quality control method combined accuracy and simplicity; however, some doubt exists at the present time regarding the reproducibility of the test method among different laboratories. Based on limited data, the numerical limits of these control methods which would allow satisfactory operation of most current turbojet engines were established at an NACA K factor of 310, or a smoking tendency of 13.0.

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APPENDIX A

FUEL QUALITY CONTROL TESTS

Introduction

The following is a brief discussion of the various test methods considered in the foregoing report and includes the reproducibilities which may be expected and the skills, apparatus, and times required for their execution. Three categories of test methods are included: (a) the conventional hydrocarbon fuel analyses, (b) factors, or related fuel properties, which can be derived from these analyses, and (c) special empirical laboratory tests which have been developed primarily for evaluating the carbon-deposition tendencies of turbojet fuels.

Fuel Analyses

Distillation, gravity, aniline point. - The tests for distillation, gravity, and aniline point are well established A.S.T.M. procedures and require only average laboratory skills and modest amounts of equipment and time. All can easily be run in any petroleum testing laboratory. The A.S.T.M. distillation (reference 16) requires about 1 hour for setup and execution and several tests can be run simultaneously by a skilled operator. Gravity (reference 17) can be determined in a few minutes, and aniline point (reference 18) in about 1/2 hour after the preliminary distillation of aniline (required daily) which takes about one hour. The A.S.T.M. required reproducibilities for these tests are (1) between 5° and 10° F for the 50-percent distillation temperature for JP-3 and JP-4 type fuels, (2) 0.5° API for gravity, and (3) 0.72° F for aniline point. The reproducibilities referred to herein are the maximum differences allowed among the results of different operators using different apparatus.

Hydrogen-carbon ratio. - The hydrogen-carbon ratio can be determined by the Liebig combustion train, by the A.S.T.M. lamp method, or by beta or gamma ray absorption. A large number of combustion-train methods can be found in the literature using micro, semimicro, or macro scale setups and the equipment costs vary considerably. The macro scale train at the NACA laboratory requires about 4 hours per determination and one operator can easily run two trains simultaneously. The micro and semimicro trains require 1 to 2 hours per determination but it is questionable whether more than one train could be operated effectively by most laboratory personnel. The reproducibility to be expected from Liebig train hydrogen-carbon analyses appears to vary with the operator. Results at the NACA invariably check within 0.001 hydrogen-carbon ratio units but perhaps a reproducibility of better than 0.002 units should not be expected among laboratories. The A.S.T.M. lamp method (reference 19) uses a fairly simple burner and absorber setup and requires

about 4 hours per determination, although a multiple unit could easily be handled by a skilled operator. The A.S.T.M. required reproducibility is 0.06 percent hydrogen, equivalent to about 0.001 hydrogen-carbon ratio units. The beta and gamma ray absorption methods are a recent development of the Engineering Research Department of the Standard Oil Company (Indiana) and little information concerning the equipment cost or the type of personnel required for its operation is available. The time required per determination is probably less than 1/2 hour and the probable error for the beta ray method is 0.035 percent hydrogen or 0.0005 units of hydrogen-carbon ratio.

Total aromatics. - Total aromatics are currently being determined under the MIL-F-5624A (JP-3 and JP-4) procurement specifications by the A.S.T.M. sulfonation and bromine number method (reference 20). The accuracy of this test method is questionable, since some jet fuels may have bromine numbers exceeding the value permitted by the scope of the A.S.T.M. method. The A.S.T.M. is studying improved methods for this analysis and the California Research Corporation's fluorescent indicator method (unpublished) appears most attractive at present. This method has very modest equipment requirements and takes about 4 hours per determination, although one operator can run six or more tests simultaneously. Reproducibility of 1 percent is expected.

High-boiling aromatics. - The determination of aromatics boiling above 400° F requires a distillation prior to analysis of the plus 400° F fraction. This distillation requires from 1 to 8 hours depending on the desired sharpness of separation; the subsequent aromatic analysis requires from 4 to 12 hours using different procedures. The procedure for the determination of the plus 400° F aromatics has not been standardized and no estimate can be made at present as to the time requirements or reproducibility of this determination.

Naphthalenes. - The naphthalenes, as a special class of aromatics, have been determined polarographically (reference 21), by ultraviolet absorption (reference 22), or from refractivity intercept (reference 23). The first two methods require equipment which probably is not available in many testing laboratories and would take 1 to 2 hours per determination after the instruments have been calibrated. Refractivity intercept is a function of refractive index and specific gravity and probably could be determined in most testing laboratories in about 1 hour. All three methods should be reproducible to about 25 percent of the amount of naphthalenes present.

Related Fuel Properties

NACA K factor. - The NACA K factor (reference 5) is given by

$$K = (t + 600) (0.7) \frac{H/C - 0.207}{H/C - 0.259}$$

where

t the volumetric average boiling point in °F

H/C the hydrogen to carbon weight ratio

The reproducibility of the K factor is dependent upon the reproducibility of both variables. For a typical borderline quality fuel ($t = 330$, $H/C = 0.155$, and $K = 325$), and maximum deviations of $\pm 5^\circ$ F in t and ± 0.002 in H/C , a maximum deviation of 8.0 K units and a probable deviation of 6.5 K units is obtained. Actual deviations among 4 laboratories, for 4 different fuels (omitting one result obviously in error) are as follows (unpublished data):

	Average deviation	Maximum deviation
t, °F	3.2	8.0
H/C	0.0014	0.0035
K	5.7	14.0

Aniline-gravity constant. - The aniline-gravity constant is the product of the aniline point in °F and the API gravity. For a borderline fuel (aniline point, 100° F; API gravity, 45; aniline-gravity constant, 4500) and the A.S.T.M. specified reproducibilities (noted above), a maximum expected deviation in aniline-gravity constant of 82, and a probable deviation of 59 is obtained.

Estimated hydrogen-carbon ratio. - Several correlations have been proposed for estimating the hydrogen-carbon ratio from other fuel properties. Watson (reference 8) and Linden (reference 9) have presented correlations for the estimation of hydrogen-carbon ratio from distillation and gravity. A comparison of these correlations for 76 fuels is presented in figure 13. The somewhat greater accuracy obtained with the Watson correlation (fig. 13(a)) can be further improved for jet type fuels by adding 0.004 units to the calculated hydrogen-carbon ratio. The correlation of carbon-deposition data with gravity and volumetric average boiling temperatures presented in figure 5 was obtained from this corrected correlation. Thus, the curves of constant gravity were determined as follows: assuming that the fuels contain only carbon and hydrogen, and that the mean average boiling temperature of a fuel is approximately equal to the volumetric average boiling temperature, the hydrogen-carbon ratio was calculated from the Watson correlation equation (reference 8)

$$\text{Percent H} = 14.2 + (0.173 \times ^\circ\text{API}) - \frac{7250}{(\text{Mean average B.P., } ^\circ\text{R})}$$

corrected by the addition of 0.004 hydrogen-carbon units. The hydrogen-carbon ratios obtained for various gravities and volumetric average boiling temperatures were then substituted in the K equation of reference 5.

Linden (reference 9) has also presented a correlation for the estimation of hydrogen-carbon ratio from distillation, gravity, and aniline point. The deviations of the calculated hydrogen-carbon ratio from the experimentally determined ones are shown graphically in figure 14. Because both aniline point and hydrogen-carbon data were unavailable for the majority of fuels presented in figure 13, a number of fuels for which the additional analytical data are available are included.

Considering only hydrogen-carbon ratios between 0.14 and 0.17 (the probable range for jet-type fuels), the average and maximum deviations of estimated hydrogen-carbon values from analyzed hydrogen-carbon values are as follows for each of the three correlation methods discussed:

Method	Deviation among all points between 0.14 - 0.17 H/C		Deviation among best 90 percent of points	
	Average	Maximum	Average	Maximum
Distillation and gravity (Watson)	0.0042	0.030	0.0027	0.011
Distillation and gravity (Linden)	0.0057	0.027	0.0044	0.012
Distillation, gravity, and aniline (Linden)	0.0042	0.011	0.0036	0.008

Smoke and Carbon Tests

Smoking tendency. - A simple wick lamp has been used to determine the maximum height of a smoke-free flame. Smoking tendency of a fuel is defined as $\frac{320}{h}$, where h is the maximum flame height in millimeters. The test has very modest equipment requirements and can easily be completed in 15 minutes. The only indication of its reproducibility among laboratories results from a comparison of flame heights obtained by Phillips Petroleum Company and by NACA on four Coordinating Research Council fuels.

These results are listed below:

Fuel	Flame height (mm)	
	Phillips Petroleum Company	NACA
RAF 26-50	21	24
RAF 27-50	62	67
RAF 28-50	30	27
RAF 29-50	51	57

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Some increase in reproducibility might be obtained by calibrating the lamp on binary fuel blends and reporting smoking tendencies as smoke lamp numbers similar to the use of isooctane and *n*-heptane in octane number determinations. This procedure would tend to minimize the effect of apparatus and operating variables. Preliminary investigations have been conducted at the NACA laboratory using mixed xylenes and *n*-decane as the rating pair. The resulting blending curve of flame height versus composition is shown in figure 15. Also shown in this figure are the flame heights at the smoking point for eight of the fuels listed in Table I(a). The curve shows, for example, that fuel A with a flame height of 26.2 millimeters has a xylene rating of 28, and presumably this rating could be closely reproduced in other laboratories by bracketing the sample with blends of the same reference fuels. Since the xylene - *n*-decane pair may not be desirable from an availability standpoint, other hydrocarbons may be chosen as the reference fuels.

Flame plate. - In the flame-plate test, fuel is delivered dropwise to the surface of a tared stainless steel plate maintained at a constant elevated temperature (reference 3). The vaporized fuel is ignited by a Bunsen burner pilot and, after a specified amount of fuel is burned, the plate is reweighed to determine the amount of deposits. The test requires approximately 6½ hours. From 5 to 4796 milligrams of deposit have been obtained in burning 400-milliliter samples of widely varying types of fuels (reference 10). Flame plate data are too limited to obtain a conclusive estimate of the reproducibility.

Pot burners. - In the 5-inch pot burner test (unpublished information from the Texas Company) 1½ pounds per hour of fuel are burned with 37 pounds per hour of 125° F air for 6 hours and the resulting carbon deposits are scraped from the burner and weighed.

Four widely differing fuels yielded from 0.3 to 3.5 grams of carbon in this test with precisions of the order of ±20 percent (unpublished Texas Company data). No estimate can be made concerning the probable

reproducibility for various units in various laboratories. Apart from the lack of general availability of this unit in most laboratories and the uncertain reproducibility of the method, this test appears to require too much time, fuel, and air to be readily acceptable as a control laboratory test.

SUMMARY

Considering the apparatus requirements, ease, and times for execution, degrees of standardization and reproducibilities, the laboratory tests considered herein can be divided into the following four groups, in order of decreasing desirability:

1. Distillation, gravity, and aniline point are all A.S.T.M. standardized techniques which could easily be run with the equipment and personnel available in any petroleum testing laboratory. The expected reproducibilities are well established for all these tests.

2. Lamp hydrogen is also an A.S.T.M. procedure but is not as commonly used as are the tests listed in group 1. Its performance, however, should present no major problem to most testing laboratories.

3. The percent aromatics (by California Research Corp, Fluorescent Indicator method) and the smoke lamp tests are both simple procedures and well suited for laboratory control purposes. However, neither method has been standardized in the A.S.T.M. manner and at present they may not be acceptable for fuel procurement purposes for this reason.

4. The gamma and beta ray absorption methods for hydrogen concentration, the combustion train hydrogen-carbon analysis, the percent aromatics boiling above 400° F, the percent naphthalenes, the flame plate, and the pot burner methods are all undesirable from a control laboratory standpoint at the present time. None have been standardized regarding equipment and operation and their reproducibilities have not been established. In many cases the equipment and skills required appear to be serious obstacles in their use as laboratory control tests. However, the beta ray absorption method, in particular, appears quite promising and may become available as a rapid and accurate method for the routine determination of hydrogen-carbon ratio.

APPENDIX B

SERVICE EXPERIENCE AT PATUXENT RELATED TO

CARBON DEPOSITION

By C. C. Singleterry and H. E. Alquist

INTRODUCTION

In order to summarize Navy experience with JP-3 fuel which might indicate the effect of carbon deposition on actual aircraft operation, a study has been made of the operational reports from the Naval Air Test Center, Patuxent River, Maryland, since June 1949, when two types of aircraft started operation on JP-3.

During the first year of operation on JP-3 at Patuxent an attempt was made by the Fuels Branch, Bureau of Aeronautics, to cover a wide range of fuel quality in order to determine the suitability of JP-3 for service operation. Because of this broad range in fuel quality and relatively complete reporting of flight experience with the fuels, primary emphasis is given to the results of tests conducted between June 1949 and May 1950. This material has been supplemented by a review of the Patuxent flight results since May 1950 when JP-3 was used as "shop fuel" at Patuxent.

Letter reports from Patuxent to the Bureau of Aeronautics and conversations with test pilots and power-plant maintenance staff were used as source material for this report. Although this constitutes the best information available on service experience with JP-3, sufficient information has not yet been obtained to define clearly the effect of changes in fuel quality on carbon deposition and, in turn, aircraft reliability and engine maintenance.

DESCRIPTION OF FUELS

The following table includes the inspection data for each batch of JP-3 used at Patuxent between June 1949 and May 1950. Since a fuel analysis was made monthly by the Naval Engineering and Experiment Station of each of the storage tanks of JP-3, each inspection value shown in this table is an average of at least three reports. Included in the table are the NACA K factors (reference 5) obtained by calculating hydrogen-carbon ratios by a modified Watson procedure described in appendix A. The H/C ratios and NACA K factors were also determined for each inspection report and then averaged for this table.

	Minimum quality		Procurement stock	Maximum quality
	No. 1	No. 2		
Air-jet gum	8.3	11.1	5.2	1.5
Accelerated gum	21.6	42.3	9.0	2.1
Sulfur, percent	0.333	0.491	0.112	0.027
Vapor pressure, lb/sq in.	5.4	5.2	6.1	4.8
Specific gravity	0.793	0.800	0.768	0.741
Aromatics, percent	26.0	29.0	15.3	9.0
Bromine number	6.0	5.0	2.0	2.0
Distillation temp., °F				
Initial boiling point	106	105	110	118
10	148	148	172	177
30	262	291	235	213
50	350	372	296	246
70	424	431	401	309
90	490	500	490	433
End boiling point	555	557	561	495
Hydrogen-carbon ratio	0.1507	0.1491	0.1621	0.1709
NACA K factor	340.6	350.0	297.0	250.0

It will be noted that the JP-3 fuels have been separated into three groups, roughly according to quality. The JP-3 designated Procurement Stock was included in the flight test program as being intermediate in quality and typical of the JP-3 fuels normally obtained on the east coast. Batch number 1 of minimum quality is Air Force Fuel PPF-47-4. It is interesting to note that the designation minimum and maximum are appropriate in view of the corresponding NACA K factors. In addition it appears that an extremely broad range of JP-3 fuel quality was covered.

The following table includes abbreviated inspection data for the batches of JP-3 used as shop fuel at Patuxent since May 1950. As in the case of the preceding table, NACA K factors were obtained by calculating hydrogen-carbon ratios by the procedure described in appendix A (modified Watson procedure). After September 1950, consumption of JP-3 had risen to the point where considerable variation in fuel quality occurred from month to month. The period September through February was chosen as particularly suitable for supplementary review of flight experience in view of the quantity of JP-3 consumed (about 620,000 gal) and the variation in fuel quality occurring. It will be noted, however, that no fuel used during this time would appear to be as poor as the minimum-quality stock tested earlier.

Date	7/6/50	8/10/50	9/8/50	10/5/50	11/3/50	12/5/50	1/3/51	3/2/51	4/4/51
Gravity	0.742	0.744	0.745	0.756	0.760	0.758	0.784	0.748	0.778
Distil- lation temp., °F									
10	148	150	150	161	160	160	168	140	183
30	173	179	181	198	204	216	231	313	262
50	208	215	219	237	264	269	299	361	320
70	278	290	293	299	355	363	425	391	384
90	453	459	460	464	450	449	481	437	457
H/C	0.1644	0.1644	0.1643	0.1602	0.1610	0.1631	0.1540	0.1758	0.1583
K factor	268.5	268.5	272.0	289.0	291.5	285.8	325.8	244.0	312.0

The dates listed in this table are the dates upon which a fuel sample was drawn from the storage tanks at Patuxent.

SERVICE EXPERIENCE

(June 1949 to May 1950)

Engine A

Flight experience was obtained on Engine A with both batches of the minimum-quality fuel, procurement stock, and the maximum-quality JP-3.

When the minimum-quality batch number 1 JP-3 was first used, it was impossible to start the engine after six hour's operation because of fouled spark plugs. The fouling was eliminated by modifying the air flow and increasing the size of the drain holes in the plugs. Thereafter no starting difficulties were reported. After consuming about 24,000 gallons of this fuel, Patuxent reported "considerable" carbon deposition on the combustion-chamber liners. Specifically, "the deposits were not consistent in either location or severity of build-up, and they seemed to be more severe during the 15.3 flight hours which were devoted to air-start experimentation." It was also reported that in using this batch the aircraft left a distinct trail of black smoke in flight. This was considered to be "undesirable from a tactical viewpoint."

About 24,000 gallons of maximum-quality JP-3 was tested next in the same aircraft. "The amount of carbon deposition in the combustion section was not considered to be objectionable. Carbon deposits were found on the second inner section of the outer burner and were of an average depth of one-quarter inch."

Tests subsequently conducted on batch number 2 of the minimum-quality fuel revealed "that carbon deposition was of such severity, regardless of the type of operation, that burning continued after engine shut down. This is believed to have resulted from the saturation of the carbon deposits with fuel." Cracking of the combustor chamber liners was found and was attributed, to some degree, to the use of JP-3 since no reports of similar failures had been received from operating squadrons using AN-F-48 fuel.

The tests conducted on procurement stock showed it to be "more satisfactory for use" than either batch 1 or 2 of the minimum-quality JP-3. "The carbon deposits were not as severe as those encountered with the minimum-quality fuel but residual burning (burning after engine shut down) will be experienced with this fuel" on this type engine. Another indication of the suitability of the maximum-quality and procurement stock JP-3 is that Patuxent recommended operational use of these fuels in this type aircraft.

Engine B

In 130 hours of operation on an airplane using Engine B with about 40,000 gallons of minimum-quality JP-3 (batch 1), no difference in aircraft performance was noticed between AN-F-48 and AN-F-58. However, as was the case when Engine A in other type aircraft used this fuel, a "distinct trail of black smoke was left in flight." "During the 120-hour engine check, excessive carbon deposits were found on several fuel nozzles, and the majority of combustion liners were buckled sufficiently to require replacement. This engine had been operated for 41.5 hours on AN-F-48 and 81.6 hours on AN-F-58 fuel." In a subsequent report to the Bureau of Aeronautics, it was stated that cracking and distortion of the combustion liners of Engine B were not believed to be caused by this fuel because of the numerous reports from squadrons using this engine of liner failures which occurred while AN-F-48 was used.

After 56.5 hour's operation on the maximum-quality fuel, it was reported that "carbon deposition was negligible."

Although not verified by a detailed report of number of engine hours on procurement stock JP-3, it appears that Engine B was operated long enough on this fuel that Patuxent recommended operational use of this fuel in this type aircraft. The same recommendation was made for the maximum-quality fuel.

Engine C

"No adverse effect on the combustion chamber liners, nozzle diaphragms, and turbine wheels" has been noted in operation of aircraft with Engine C with procurement stock JP-3.

REDACTED

Engine D

"Carbon deposits have not been objectionable" when procurement stock JP-3 was used in the aircraft powered by Engine D. "Occasional burning after engine shutdown has been experienced."

SERVICE EXPERIENCE

(May 1950 to Present)

It will be recalled from the preceding table that the JP-3 "shop fuels" at Patuxent since May 1950 all had lower NACA K factors than either batch of minimum-quality JP-3. If the degree of carbon deposition in service tests correlated with K factor in the same manner that carbon deposits increase with increasing K in laboratory tests, no reports of severe carbon depositing difficulties would be expected with these fuels. However, residual burning might have been anticipated with the Engine A especially during January 1951.

The total jet engine operating time at Patuxent, September 1950 through February 1951, are shown in the following table:

Engine	Operating time, hours						
	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Total
A	15	25	38	20	22	31	151
B	45	125	102	100	137	93	602
C	30	48	44	33	60	45	260
D	90	121	118	88	222	134	768
Totals	180	319	302	236	441	303	1781

Although records were not available to the authors to show exactly what fuel was used for each hour of operation, it appears that almost all of this time was put on JP-3. (According to the average fuel consumption figures for these aircraft, a total of about 620,000 gallons of JP-3 would be consumed in the 1781 hours of operation. 676,300 gallons of JP-3 were shipped into Patuxent during this period.) Although the operating time appears quite large in this table, the average time accumulated on any one aircraft is short. For example, the maximum time accumulated by one airplane in a month was 90 hours; whereas, the average operating time per month was only 10 hours for all aircraft.

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A review of the maintenance records on the jet engines used at Patuxent from September through February was made and no evidence was found of excess combustion-chamber cracking, fouled spark plugs or fuel nozzles. In discussion with test pilots at Patuxent no operational difficulties were reported with JP-3 during this period. It might be noted that the very short operating time accumulated on any one aircraft may be a contributing factor to the absence of flight interruption reports. With regard to residual burning, it was reported that "when using JP-3 fuel residual burning is more extensive than when using Grade 115/145 gasoline; however, residual burning is not considered to be the service problem that it was a year or so ago. The pilots have generally come to ignore this phenomenon."

DISCUSSION OF RESULTS

The range of JP-3 quality considered in this report is illustrated in figure 16. Essentially this figure is a plot of carbon deposits in grams versus the NACA K factor for a series of fuels tested by the NACA in a J33 combustor at a particular set of conditions. The K factor of the various JP-3 fuels used at Patuxent in the past two years has been marked; the shaded area represents the range of quality covered by the shop fuels.

It is interesting to note that the comments obtained from the pilots on the suitability of the JP-3 fuels tested between June 1949 and May 1950 reflect K factor and correlate fairly well with the carbon deposition predicted from laboratory tests. The following table shows this correlation.

Fuel number	NACA K Factor	Carbon in J33 (grams)	Service Comment
1	250.0	2.3	"not objectionable" to "negligible"
2	297.0	5.6	"some residual burning" to "more satisfactory" than fuel number 4
3	340.6	11.7	"considerable carbon but more severe during air-start work"
4	350.0	14.0	"carbon of such severity at all conditions that residual burning occurs; fuel unsatisfactory"

The differences in carbon-deposition tendencies shown in this table between various batches of JP-3 were obtained on early models of Engines A and B. Engine A was designed and developed on aviation gasoline; likewise, Engine B was developed on kerosene. It is possible that if these engines were developed on MIL-F-5161 (JP-3 referee) differences in the carbon-deposition tendencies would not be so apparent.

It will be recalled that the purpose of the review was to determine whether a service carbon-deposition problem existed and, if a problem existed, whether it could be related to fuel quality. Aside from the fuels used at Patuxent the quality of the Service JP-3 fuels has been considerably above that of the so-called minimum-quality fuels. The fact that no reports of carbon-deposition troubles have been received from service units is therefore not significant. It is clearly evident from the early Patuxent tests that a much larger volume of carbon is formed in all engines when the minimum-quality fuel is used. The extent and life of these deposits and their specific effects on engine operation or durability are more difficult to assess.

In the Patuxent tests, there were several indications of possible service troubles due to excess carbon deposits. Combustor liner buckling experienced on Engines A and B was attributed to the carbon depositing tendencies of JP-3; however, the validity of this conclusion for Engine B has since been clouded as the result of similar difficulties in squadrons using aviation gasoline exclusively. Spark plug fouling was reported on Engine A but was alleviated by modifying the air flow around the plug. Residual burning after shut down was reported on Engine A and was attributed to a combination of dripping fuel nozzles and carbon deposits. More recent service reports indicate that this trouble is experienced with all JP-3 fuels to some extent and that at present many pilots are ignoring it since the fire usually goes out within 10 or 15 seconds. Whether a few recent reports of Engine A combustion chamber warping and cracking when JP-3 is used are related to residual burning has not been established. Other possible sources of service troubles include nozzle deposits, smoke trails, and the difficulties encountered in inspecting critical engine parts in the presence of heavy carbon deposits.

In summary, there are indications of several types of carbon-deposition difficulties with minimum-quality fuel but the problems have not yet been clearly defined by service experience. It appears that further tests on minimum-quality fuel are needed and, in view of the wide variability in the occurrence and nature of carbon deposits, it is recommended that the tests include operation of a group of aircraft over a period of several months.

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TABLE I - FUEL ANALYSES AND CARBON-DEPOSITION RESULTS

(a) J33 combustor



Fuel	A.S.T.M. distillation (°F)						Volumetric average boiling temperature (°F)	Specific gravity 60°/60° F	Gravity (°API)	Aniline point (°F)	Aniline- gravity constant	Aromatics* (percent by volume)	Percent aromatics + 0.1 times 80-percent evaporation temperature	Smoking tendency 320/h	Hydrogen- carbon ratio	NACA K ^{a,b}	Dicyclics (percent by volume)	Carbon deposition (grams)			
	percentage evaporated																	1	2	3	Average
	10	30	50	70	80	90															
A	157	230	314	388	427	473	312	0.759	58.5	111.9	5,880	19	81.7	12.2	0.163	291	3.0	5.9	6.0	6.5	6.1
B	157	248	332	410	480	500	329	.775	51.1	—	—	19	84.0	12.9	.161	304	4.1	7.3	7.5	—	7.4
C	164	273	370	437	484	501	349	.806	44.1	—	—	29	75.4	24.6	.150	347	12.8	11.4	15.0	—	15.2
D	358	568	578	387	394	406	378	.833	36.8	—	—	15	54.4	17.2	.154	345	—	12.6	11.8	—	12.2
E	159	270	310	383	434	468	320	.785	48.8	109.4	5,340	24	87.4	15.3	.155	322	—	8.8	9.6	10.1	9.8
F	180	182	204	222	250	245	301	.705	69.8	150.6	10,620	3	26.0	4.6	.183	177	—	1.3	1.3	—	1.3
G	320	329	332	340	346	358	335	.786	48.5	151.0	6,350	16	50.6	11.6	.164	295	—	9.1	8.8	9.1	8.6
H	151	260	358	433	458	502	341	.740	59.8	180.1	10,770	3	48.6	5.6	.183	207	—	3.3	4.1	3.5	3.6
I	182	314	368	454	478	515	372	.802	45.0	—	—	23	70.8	—	.154	342	—	13.9	11.3	—	12.6
J	220	311	420	463	485	513	393	.810	43.2	—	—	18	64.5	—	.158	335	—	12.1	14.5	—	13.3
K	221	258	288	318	334	353	298	.800	45.4	50.8	2,310	37	70.4	27.8	.142	345	—	18.8	14.0	—	15.4
L	225	332	341	351	359	369	343	.768	52.2	129.9	8,910	1	38.9	6.0	.176	261	—	0.9	0.9	—	0.9
M	322	324	324	328	327	328	325	.874	30.4	—	—	88	130.7	50.0	.116	412	—	22.6	22.7	—	22.7
N	242	303	331	359	373	398	327	.787	48.4	117.5	5,885	20	57.5	—	.158	311	—	8.8	8.4	—	8.5
O	247	304	333	356	373	403	328	.777	50.8	128.5	8,580	15	50.3	—	.164	294	—	5.4	6.0	—	5.7
P	177	234	294	359	387	433	299	.756	56.8	137.1	7,650	9	45.7	8.7	.171	258	—	3.3	3.2	3.5	3.4
Q	230	338	394	420	438	457	368	.785	48.7	142.2	8,950	13	56.6	11.2	.164	305	—	6.8	6.0	7.9	6.8
R	254	330	348	367	385	436	348	.822	40.7	64.0	2,605	13 ^c	51.8 ^c	22.1	.146	355	—	15.0	—	—	15.0
S	168	270	358	432	482	500	344	.801	46.2	102.0	4,610	31	77.2	24.6	.180	346	—	15.0	15.7	13.8	14.1
T	162	268	350	413	444	477	328	.791	47.4	108.0	5,120	26	70.4	18.8	.153	351	—	10.3	10.1	11.6	10.7

^aSilica gel.^bReference 5.^cEstimated.

(b) 10 1/2-inch-diameter annular combustor

Fuel	A.S.T.M. distillation (°F)						Volumetric average boiling temper- ature (°F)	Specific gravity 60°/60° F	Gravity (°API)	Aromatics* (percent by volume)	Percent aromatics + 0.1 times 80-percent evapora- tion tem- perature	Smoking tendency 320/h	Hydrogen- carbon ratio	NACA K ^{a,b}	Dicyclics (percent by volume)	Carbon deposition (grams)			
	percentage evaporated															1	2	3	Average
	10	30	50	70	80	90													
A	176	180	180	184	187	192	182	0.725	63.7	—	18.7	4.2	0.177	199	—	1.0	—	—	1.0
B	359	540	344	530	560	568	345	.775	51.1	2	36.0	8.0	.179	253	—	2.0	1.6	—	1.8
C	209	210	210	211	212	215	211	.724	64.0	—	21.2	11.2	.170	256	—	4.1	—	—	4.1
D	522	522	522	528	528	525	525	.785	48.7	—	52.5	3.9	.164	345	—	2.5	—	—	2.5
E	172	172	172	172	172	173	172	.882	28.9	98	115.2	53.0	.084	378	—	27.8	38.1	34.6	35.5
F	195	212	267	325	338	333	254	.877	29.9	98	150.8	46.5	.089	405	—	56.1	—	—	56.1
G	268	270	270	270	271	272	270	.871	31.0	98	125.1	61.0	.105	402	—	44.8	—	—	44.8
H	278	278	278	278	278	281	278	.886	31.9	98	128.8	53.0	.109	400	—	52.5	—	—	52.5
I	322	324	324	328	327	328	325	.874	30.5	98	130.7	60.0	.115	412	—	51.5	81.4	—	51.5
J	330	340	350	374	410	450	369	.914	25.3	99	140.0	66.0	.104	450	27	140.5	—	—	140.5
K	440	442	444	445	447	448	444	.861	32.8	98	142.7	63.0	.132	430	—	88.3	—	—	88.3
L	458	458	460	480	480	480	459	1.016	7.7	99	145.0	70.0	.079	527	99	158.8	129.0	—	133.8
M	168	169	170	172	174	177	171	.792	47.2	44	61.4	44.0	.129	325	—	15.7	—	—	15.7
N	144	181	227	245	259	290	215	.728	62.8	16	41.9	13.9	.174	220	—	1.4	—	—	1.4
O	191	211	267	371	389	427	291	.788	53.2	6	44.9	8.4	.139	380	—	3.3	—	—	3.3
P	330	340	381	368	382	412	380	.840	37.0	54	92.2	33.7	.139	317	—	28.5	—	—	28.5
Q	345	381	371	387	400	415	378	.850	39.0	13	53.0	12.5	.162	317	—	6.8	10.9	6.4	8.0
R	460	502	512	526	535	554	517	.814	42.5	18	69.5	11.8	.165	348	—	6.8	6.0	—	6.4
S	462	490	516	548	570	604	528	.836	37.8	23	80.0	15.8	.159	378	—	31.7	—	—	31.7

^aSilica gel.^bReference 5.

TABLE II - FUEL ANALYSES AND CARBON-DEPOSITION RESULTS

(a) J31 combustor (reference 13)

NACA

Fuel	A.S.T.M. distillation (°F) percentage evaporated			Volumetric average boiling temperature (°F)	Gravity (°API)	Smoking tendency 320/h	Hydrogen- carbon ratio	Carbon depo- sition (grams)
	10	50	90					
A	334	352	393	360	45.4	12.3	0.153	2.6
B	212	228	264	235	55.6	----	.131	4.0
C	224	284	348	285	45.3	20.0	.142	15.0
D	275	276	279	277	33.5	40.0	.116	6.1
E	422	482	---	482	10.8	---	.097	4.3
F	156	256	371	261	55.9	7.3	.160	0.0
G	456	522	572	517	34.0	26.7	.148	8.4
H	326	345	375	349	41.1	10.3	.121	7.3
I	175	175	175	175	28.9	26.7	.083	3.3
J	145	200	245	197	67.2	6.4	----	0.0
K	141	209	247	199	----	5.1	----	2.0
L	336	350	360	349	----	5.8	----	.5

(b) J33 combustor (reference 24)

Fuel	A.S.T.M. distillation (°F) percentage evaporated			Volumetric average boiling temperature (°F)	Gravity (°API)	Aniline point (°F)	Aniline- gravity constant	Smoking tendency 320/h	Carbon depo- sition (grams)
	10	50	90						
A	360	384	420	388	38.0	120	4,560	12.8	10.4
B	224	284	348	285	45.3	51	2,310	16.8	13.1
C	236	294	353	294	44.5	51	2,270	12.8	11.2
D	146	302	486	311	50.0	123	6,150	4.7	4.6
E	159	207	237	201	67.4	146	9,840	5.6	5.0
F	423	522	626	524	42.7	180	7,680	5.6	8.2
G	186	380	487	351	45.4	127	5,770	5.6	6.7
H	200	224	264	229	57.5	96	5,520	9.4	39.9
I	274	275	277	275	33.5	-57	-1,910	35.6	23.3
J	158	260	370	263	55.9	121	6,760	3.5	3.3
K	341	355	364	353	55.3	183	10,120	5.3	0.9
L	152	290	481	308	51.0	118	6,020	5.2	4.3
M	177	310	455	314	46.5	83	3,860	5.7	9.4
N	190	316	480	329	46.3	96	4,450	5.9	8.1
O	168	310	465	314	47.7	82	3,910	8.2	8.9
P	334	352	393	360	45.4	120	5,450	12.3	9.6
Q	351	375	411	379	36.4	94	3,420	17.8	14.0
R	145	200	245	197	67.2	145	9,740	6.0	1.0
S	175	175	181	177	28.9	---	-----	24.6	10.0
T	152	333	485	323	46.1	---	-----	-----	13.1

(c) J31 combustor (reference 12)

Fuel	A.S.T.M. distillation (°F) percentage recovered					Volumetric average boiling temperature (°F)	Gravity (°API)	Aniline point (°F)	Aniline- gravity constant	Hydrogen- carbon ratio	Carbon depo- sition (grams)
	10	30	50	70	90						
A	430	470	492	510	528	486	47.0	181	8510	0.174	1.33
B	152	398	424	448	482	381	52.4	150	7860	.175	.20
C	406	424	442	451	468	438	30.7	103	3160	.117	23.65
D	183	189	284	420	468	309	37.2	64	2380	.113	1.85
E	370	391	417	451	494	424	35.4	---	-----	-----	2.13

TABLE II - FUEL ANALYSES AND CARBON-DEPOSITION RESULTS - Continued

(d) J31 combustor (reference 6)

Fuel	A.S.T.M. distillation (°F) percentage recovered					Volumetric average boiling temperature (°F)	Gravity (°API)	Aniline point (°F)	Aniline- gravity constant	Hydrogen- carbon ratio	Carbon depo- sition (grams)
	10	30	50	70	90						
A	177	250	310	370	455	312	49.7	115.2	5,720	0.152	95
B	188	249	286	320	360	281	48.5	78.3	3,800	.149	61
C	221	268	293	356	496	327	50.8	127.4	6,470	.162	57
D	164	255	337	401	460	323	46.5	79.9	3,710	.145	170
E	348	362	370	382	400	372	38.7	119.1	4,610	.163	47
F	326	342	351	364	382	353	46.9	129.6	6,080	.160	53
G	184	210	220	236	293	229	69.0	168.3	11,600	.184	17
H	345	362	371	384	409	374	36.7	91.6	3,360	.143	220
I	354	366	376	389	430	383	38.3	-----	-----	.150	50
J	200	253	301	358	417	306	53.1	128.0	6,795	.179	66
K	160	268	334	410	476	330	46.6	100.9	4,700	.149	193

(e) J33 combustor (reference 12)

Fuel	A.S.T.M. distillation (°F) percentage recovered			Volumetric average boiling temperature (°F)	Gravity (°API)	Aniline point (°F)	Aniline- gravity constant	Carbon depo- sition (grams)
	10	50	90					
A	389	431	479	433	44.0	153	6730	7.7
B	336	354	386	359	48.1	---	---	6.3
C	274	310	402	329	51.4	---	---	4.4
D	222	289	351	287	45.8	50	2290	11.7
E	346	368	408	374	36.2	92	3330	13.0
F	340	406	528	425	29.7	---	---	28.5
G	320	388	474	394	37.3	---	---	19.5
H	336	354	386	359	48.1	---	---	6.3
I	376	414	472	421	28.7	55	1580	25.5
J	377	409	470	419	28.6	55	1575	23.5
K	148	221	280	216	75.2	76	5720	.3
L	192	271	366	276	53.6	90	4820	5.2
M	214	278	348	280	50.5	101	5100	9.4
N	212	284	354	283	48.1	74	3560	7.9
O	372	400	---	400	30.5	57	1740	16.0
P	140	302	455	299	58.1	146	8480	2.1
Q	167	308	442	306	58.1	140	8130	2.6
R	152	370	490	337	47.5	---	---	6.7

TABLE II - FUEL ANALYSES AND CARBON-DEPOSITION RESULTS - Continued

(f) J31 combustor (reference 25)



Fuel	A.S.T.M. distillation (°F) percentage evaporated			Volumetric average boiling temperature (°F)	Gravity (°API)	Aniline point (°F)	Aniline- gravity constant	Hydrogen carbon ratio	Carbon deposition (grams)
	10	50	90						
A	176	176	177	176	49.7	85	4,220	0.167	0.8
B	208	209	209	208	71.6	176	12,600	.189	0.9
C	175	176	176	175	28.5	0	-----	-----	2.3
D	228	229	230	229	31.2	---	-----	.096	3.5
E	214	215	215	214	64.4	109	7,020	.167	3.6
F	255	345	442	347	50.8	140	7,120	.170	5.8
G	317	333	358	336	38.4	16	614	-----	7.6
H	310	340	368	339	50.1	135	6,750	-----	8.5
I	412	442	548	467	46.6	178	8,300	.172	10.0
J	350	380	422	384	36.5	135	4,930	.159	11.0
K	302	304	304	303	32.2	---	-----	-----	13.5
L	436	528	628	530	41.9	173	7,250	.167	14.5
M	390	446	510	448	28.3	---	-----	-----	16.0
N	456	456	456	456	8.0	---	-----	-----	30.6
O	450	515	608	524	30.8	136	4,190	.154	31.1

(g) J33 combustor (reference 11)

Fuel	A.S.T.M. distillation (°F) percentage evaporated			Volumetric average boiling temperature (°F)	Gravity (°API)	Aniline point (°F)	Aniline- gravity constant	Carbon deposition (grams)
	10	50	90					
A	344	380	424	383	36.9	---	-----	8.7
B	148	346	503	332	46.0	---	-----	3.0
C	140	354	510	335	47.1	---	-----	0.4
D	180	339	502	340	45.8	118	5400	4.4
E	193	375	524	364	43.7	114	4980	4.0
F	203	395	533	377	42.1	111	4670	4.8
G	200	350	506	352	44.3	108	4780	3.3
H	248	345	484	359	41.6	70	2910	3.2
I	165	333	469	322	46.0	85	3910	3.0
J	150	310	470	310	53.0	---	-----	2.8
K	158	365	519	347	41.7	---	-----	6.6
L	154	310	527	330	49.6	---	-----	4.3
M	150	310	470	310	53.0	---	-----	3.5
N	350	370	402	374	38.4	---	-----	6.5
O	154	307	466	309	50.6	---	-----	0.4
P	150	310	474	311	52.3	---	-----	2.4
Q	222	302	369	298	45.0	58	2610	3.0

TABLE II - FUEL ANALYSES AND CARBON-DEPOSITION RESULTS - Concluded

(h) J42 combustor (reference 26)



Fuel	A.S.T.M. distillation (°F) percentage evaporated			Volumetric average boiling temperature (°F)	Specific gravity 60°/60°F	Gravity (°API)	Hydrogen carbon ratio	Carbon deposition (grams)
	10	50	90					
A	165	336	480	333	0.79	46.6 ^b	0.16	74.0
B	185	316	452	321	.78	51.0 ^b	.16	19.3
C	170	370	491	353	.77	51.3 ^b	.16	22.5
D	171	369	445	336	.79	48.3 ^b	.16	29.8
E	249	381	453	366	.79	46.6 ^b	.16	50.7
F	253	212 ^a	466	264	.76	-----	.17	54.1
G	156	220	372	245	.75	-----	.16	22.7
H	153	212	482	279	.77	-----	.16	84.3
I	442	506	585	500	.85	-----	.15	28.4
J	163	330	557	350	.78	-----	.17	15.7
K	192	483	572	416	-----	-----	.16	21.3

^aValue not consistent with other distillation temperatures.^bValues not consistent with reported values of specific gravity.

(1) J33 combustor (references 28 and 29)

Fuel	A.S.T.M. distillation (°F) percentage evaporated			Volumetric average boiling temperature (°F)	Specific gravity 60°/60°F	Gravity (°API)	Hydrogen carbon ratio	Carbon deposition (grams)
	10	50	90					
A	349	385	457	397	0.811	43.0	0.161	11
B	358	412	471	414	.856	33.8	.140	45
C	361	399	446	402	.808	43.6	.160	16
D	446	508	580	511	.835	38.0	.158	26

TABLE III - FUEL VOLATILITY SPECIFICATIONS AND ANALYSES

Fuel	A.S.T.M. distillation (°F)		Reid vapor pressure (lb/sq in.)	MIL-F-5624A grade
	Percentage evaporated			
	10	90		
Specifi- cation	---	400(min)	5-7	JP-3
Specifi- cation	250(max)	---	2-3	JP-4
A	157	473	5.4	JP-3
B	157	500	5.1	JP-3
C	164	501	4.8	JP-3
D	356	405	0	----
E	159	468	6.3	JP-3
F	150	242	6.2	----
G	320	358	0	----
H	151	502	5.4	JP-3
I	182	515	5.0	JP-3
J	220	513	2.5 ^a	JP-4
K	221	353	5.7 ^a	----
L	323	369	0	----
M	322	328	0	----
N	242	398	2.0	JP-4
O	247	403	2.0	JP-4
P	177	433	6.5	JP-3
Q	230	457	2.0	JP-4
R	254	432	3.0 ^a	JP-4
S	158	500	4.5	JP-3
T	152	477	6.0	JP-3

^aEstimated values.

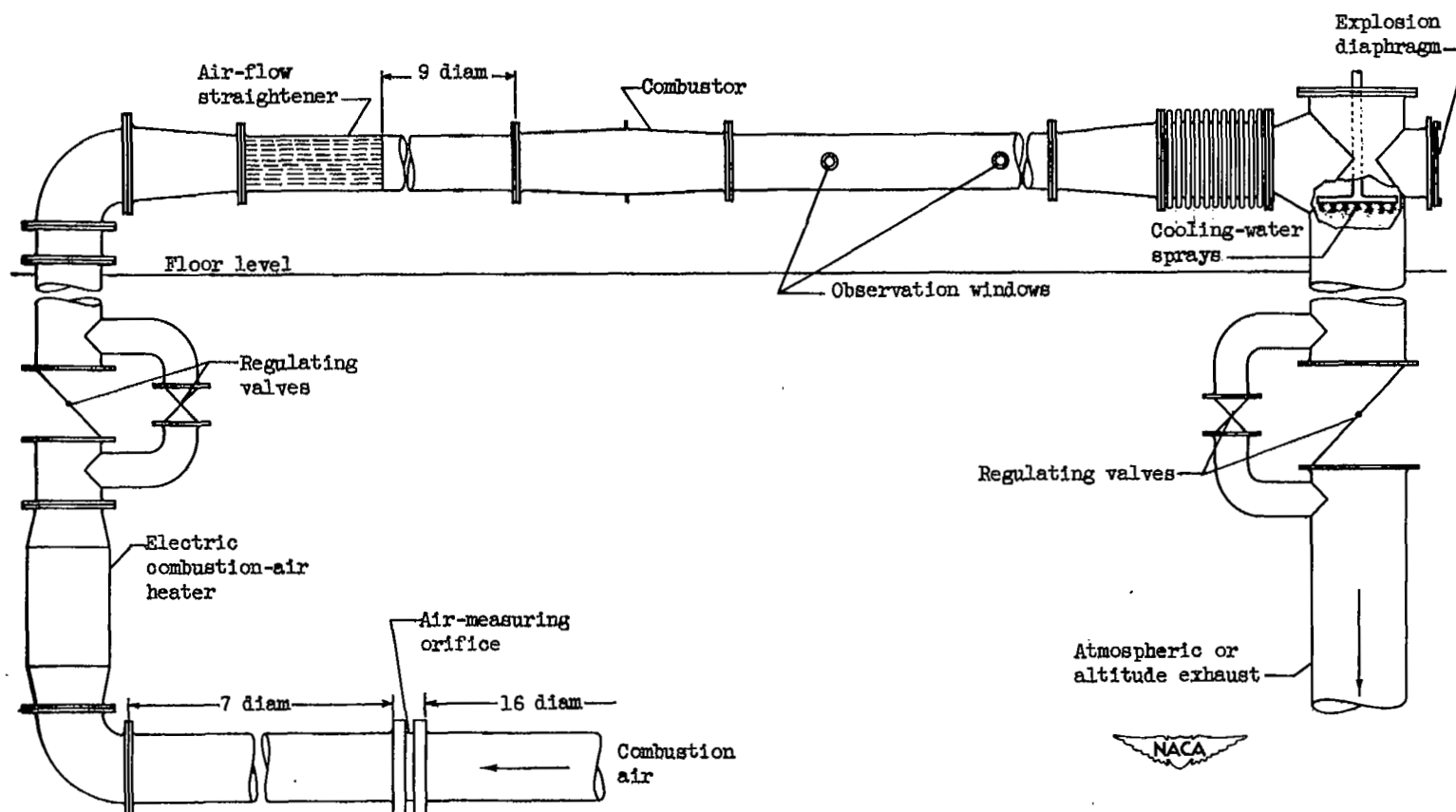
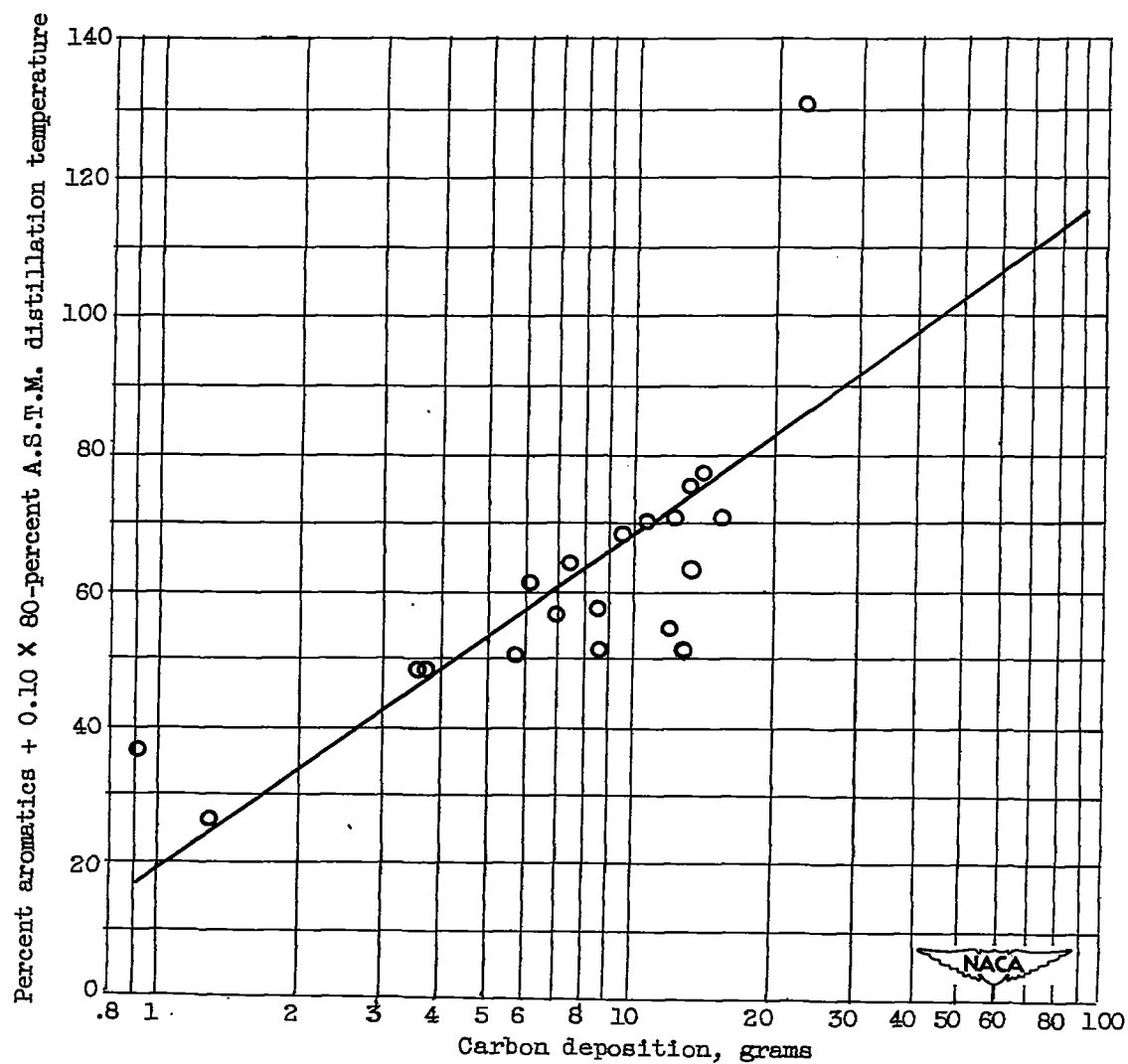
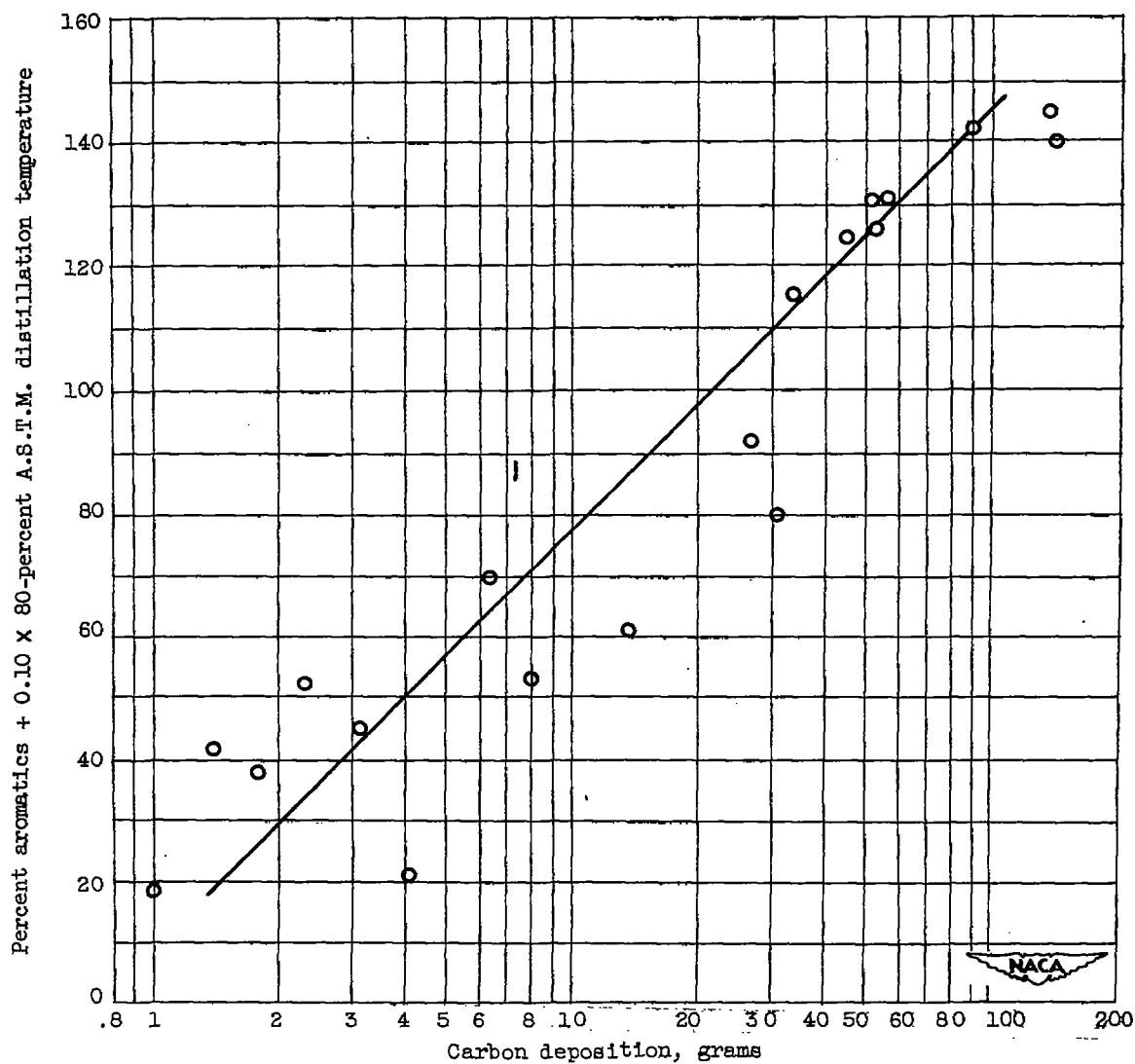


Figure 1. - Single-combustor installation and auxiliary equipment.



(a) J33 combustor.

Figure 2. - Correlation of NACA carbon-deposition data with function of aromatic content and A.S.T.M. 80-percent distillation temperature.



(b) Annular combustor.

Figure 2. - Concluded. Correlation of NACA carbon-deposition data with function of aromatic content and A.S.T.M. 80-percent distillation temperature.

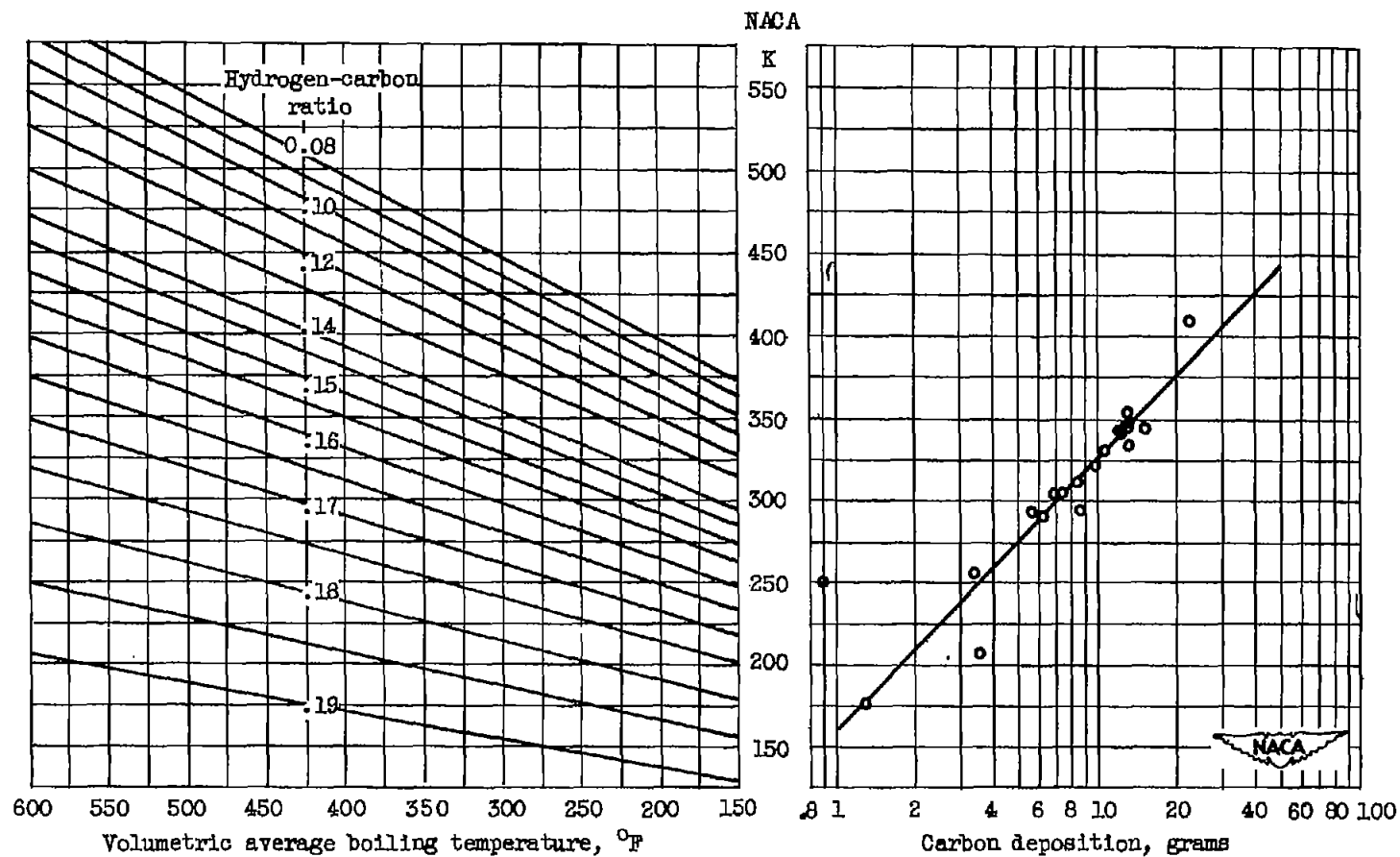


Figure 3. - Correlation of NACA carbon-deposition data with function of hydrogen-carbon ratio and volumetric average boiling temperature.

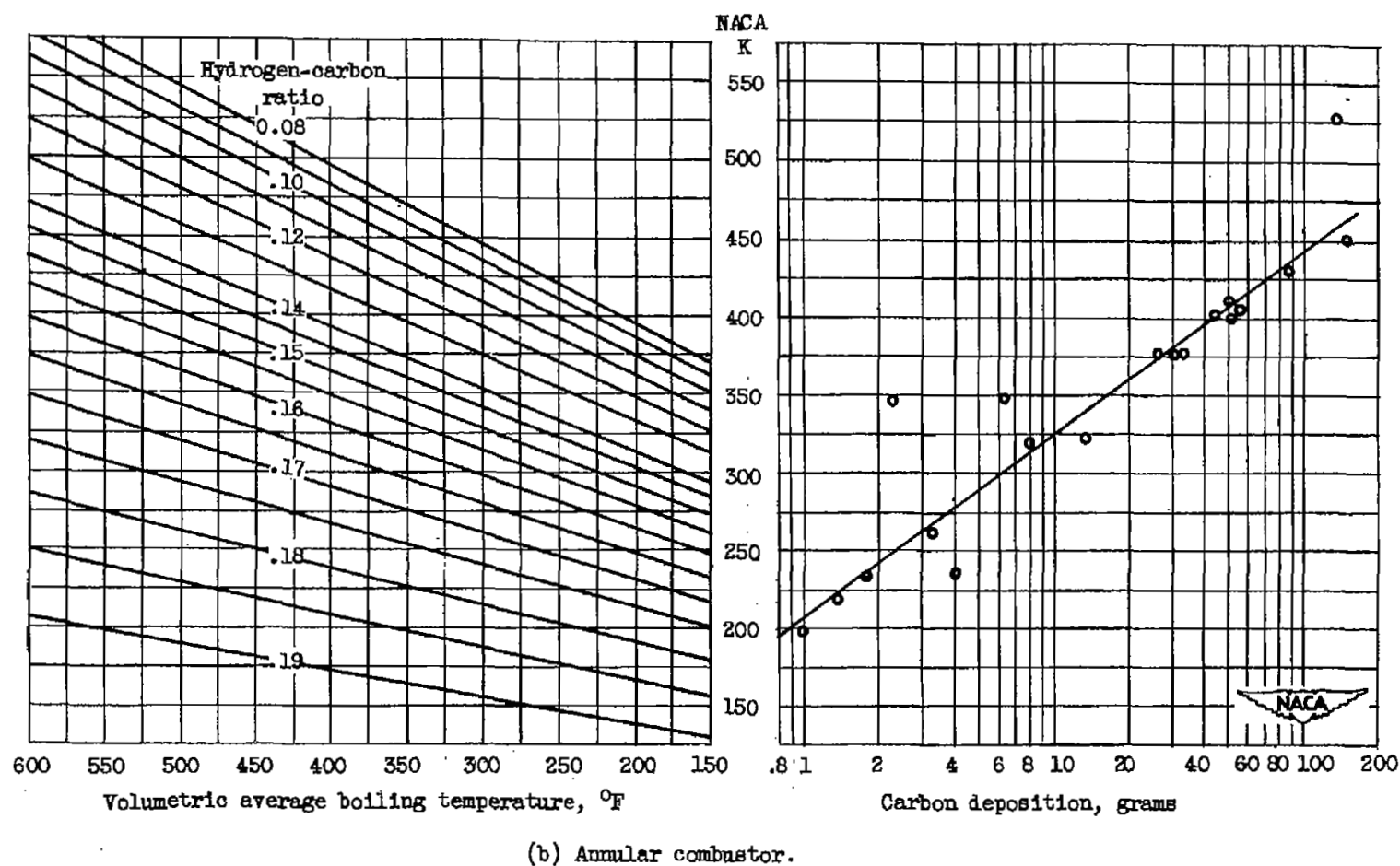
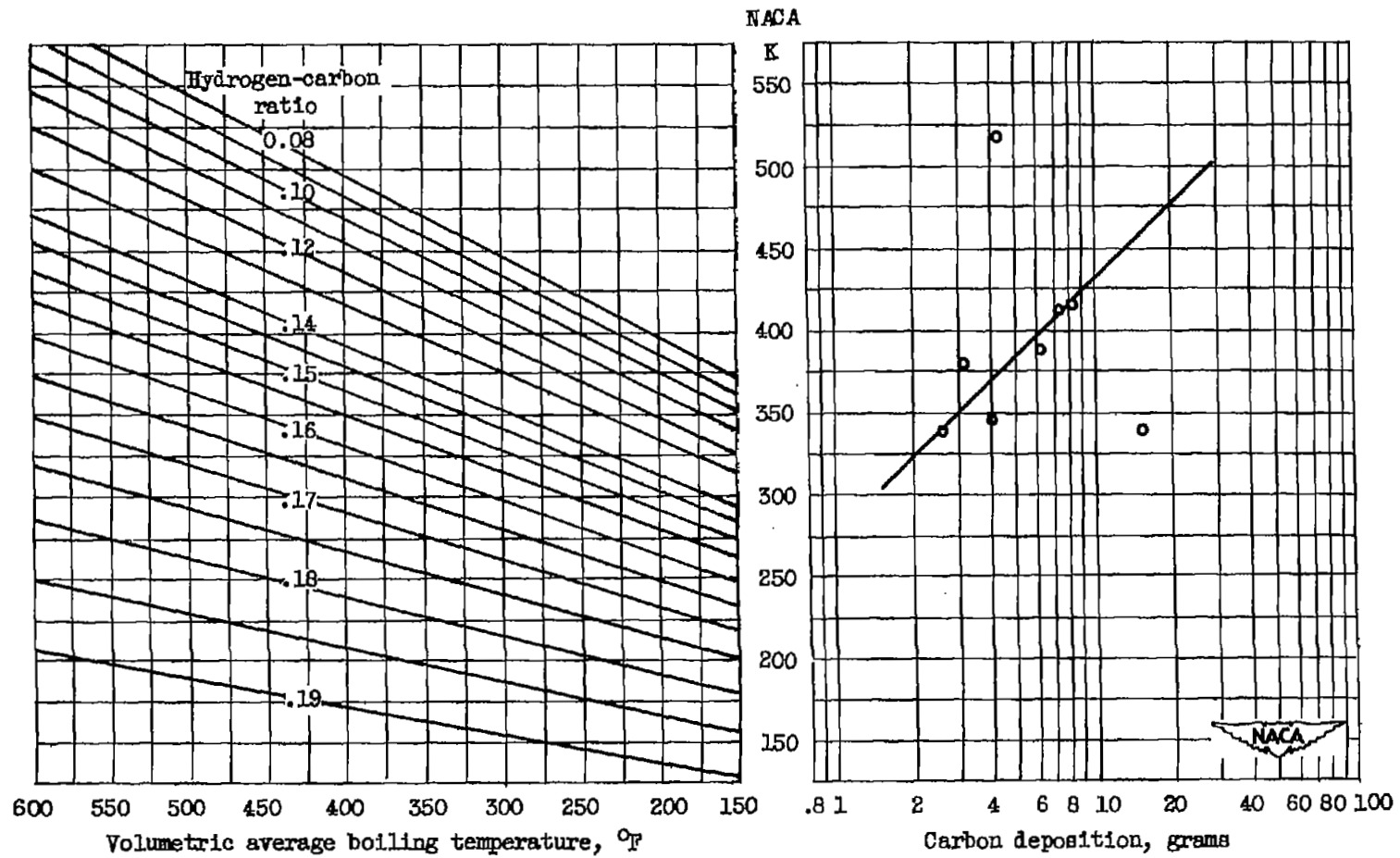
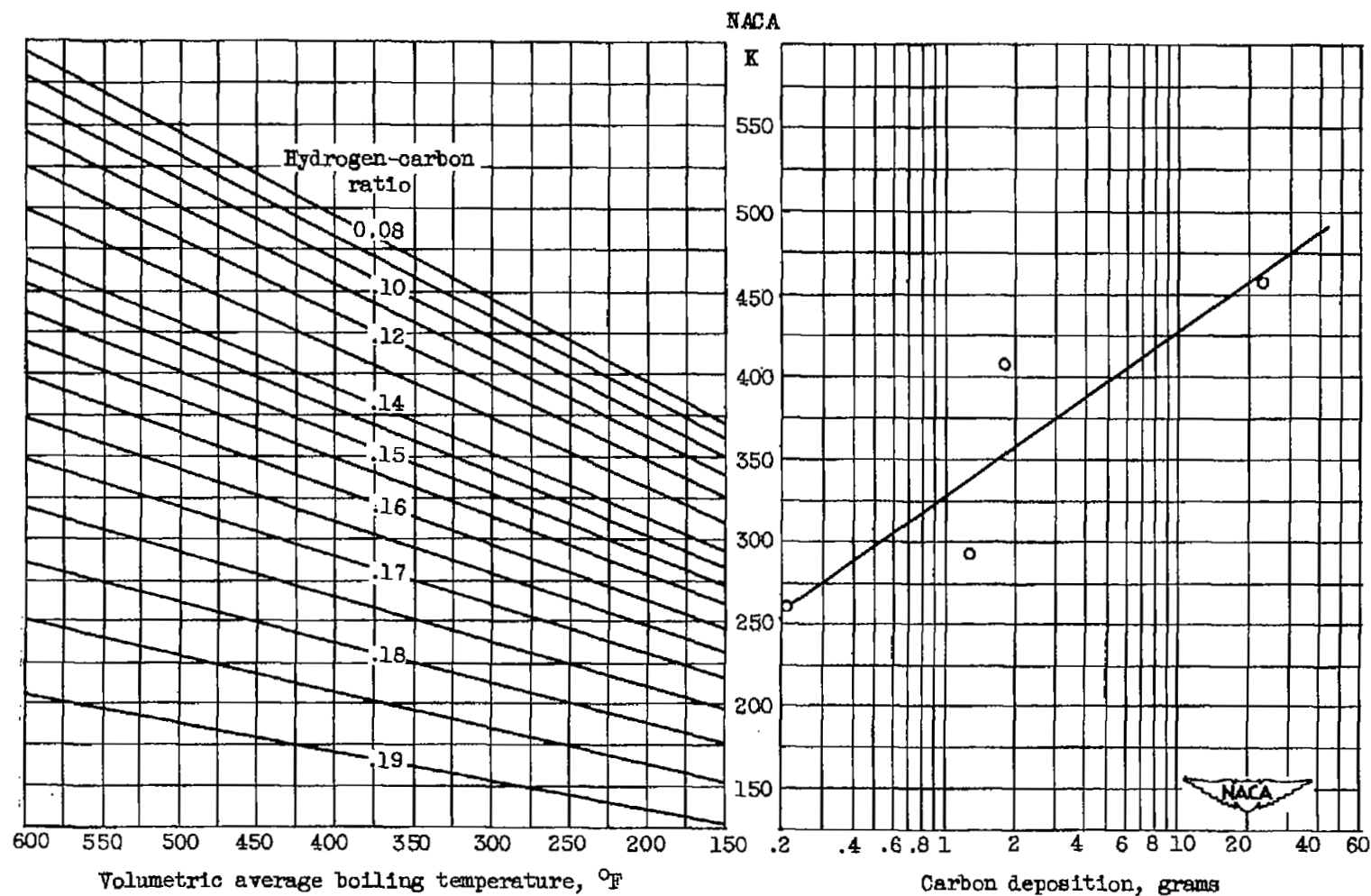


Figure 3. - Concluded. Correlation of NACA carbon-deposition data with function of hydrogen-carbon ratio and volumetric average boiling temperature.



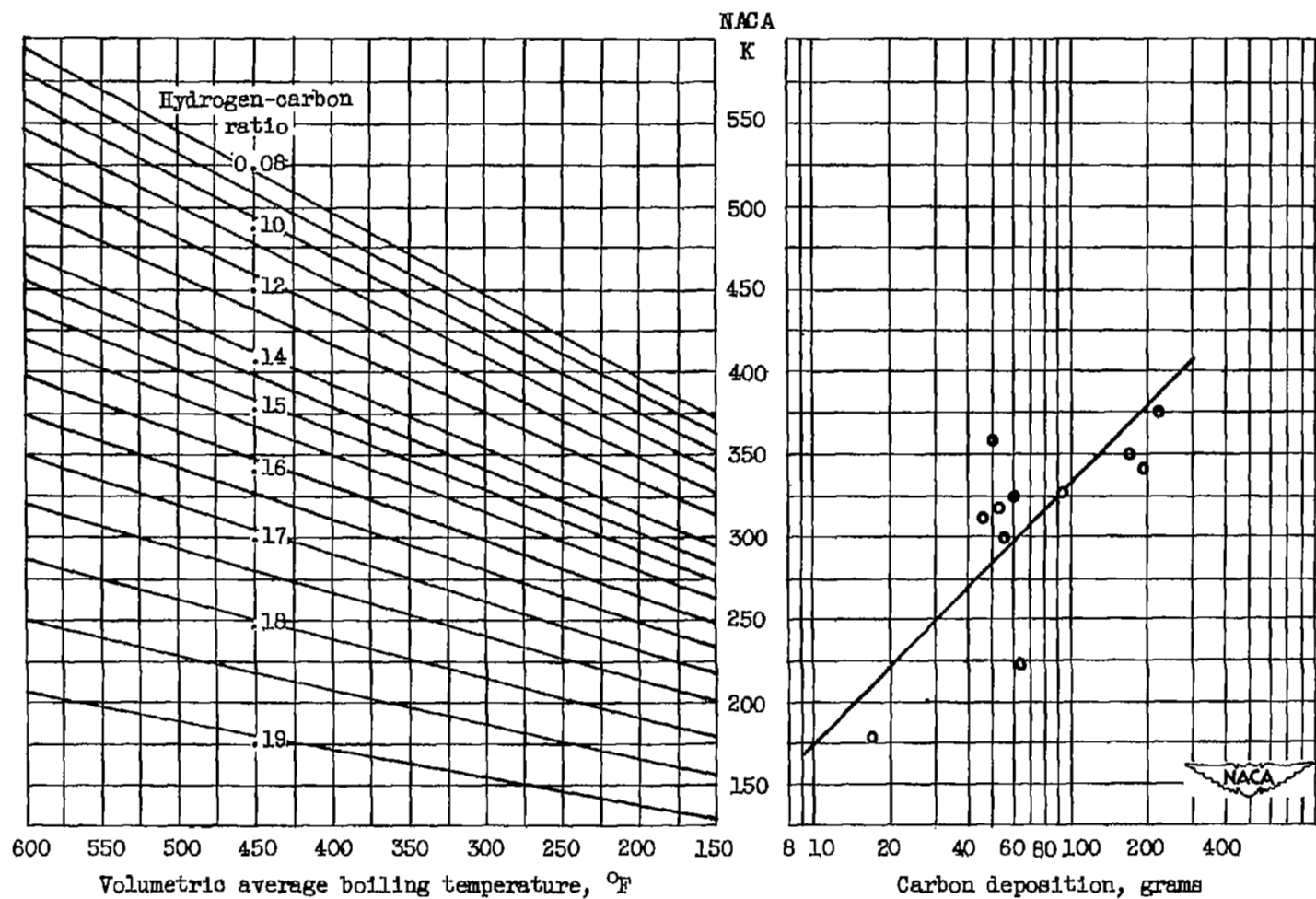
(a) J31 combustor (table II(a)).

Figure 4. - Correlation of carbon-deposition data with function of hydrogen-carbon ratio and volumetric average boiling temperature.



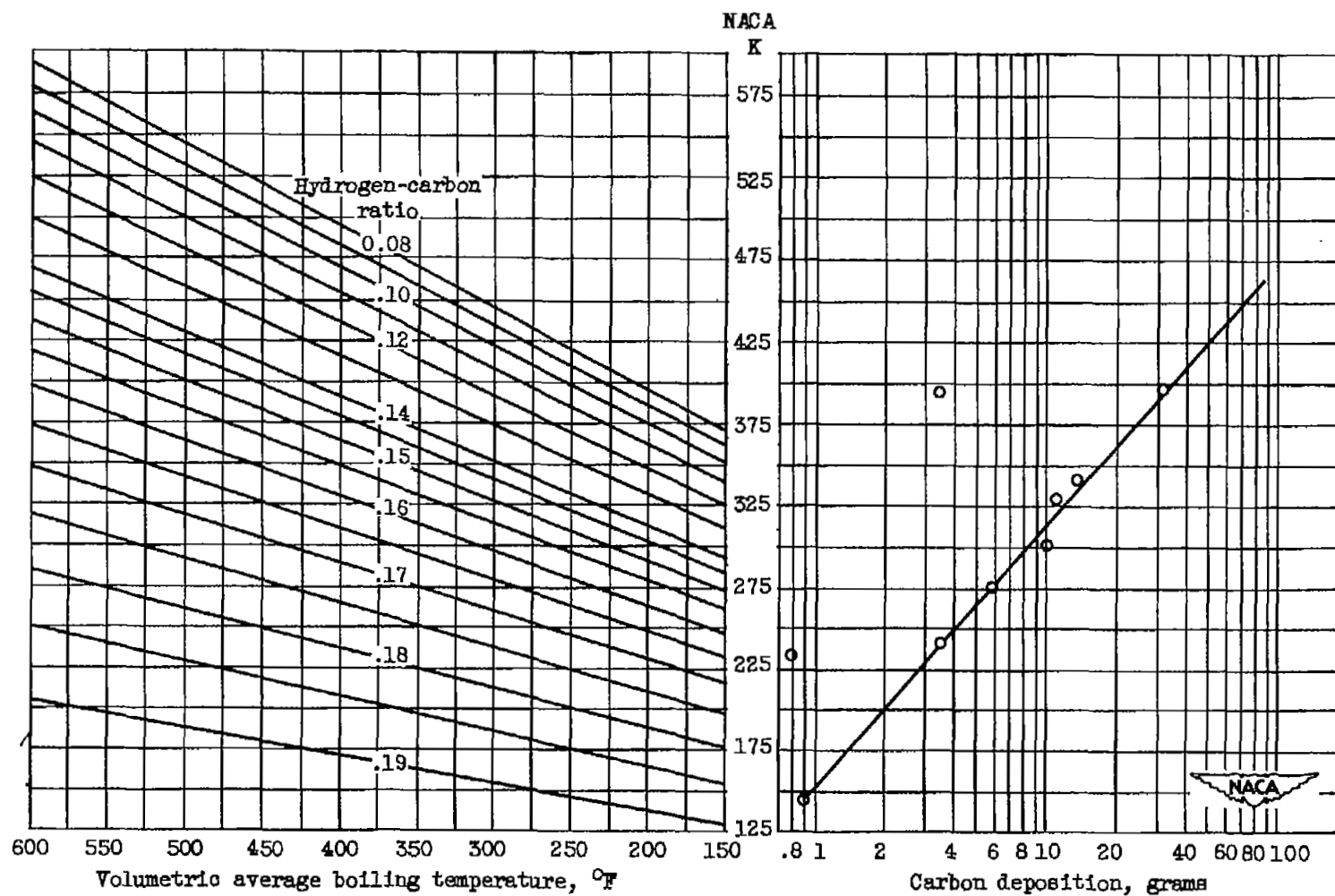
(b) J31 combustor (table II(c)).

Figure 4. - Continued. Correlation of carbon-deposition data with function of hydrogen-carbon ratio and volumetric average boiling temperature.



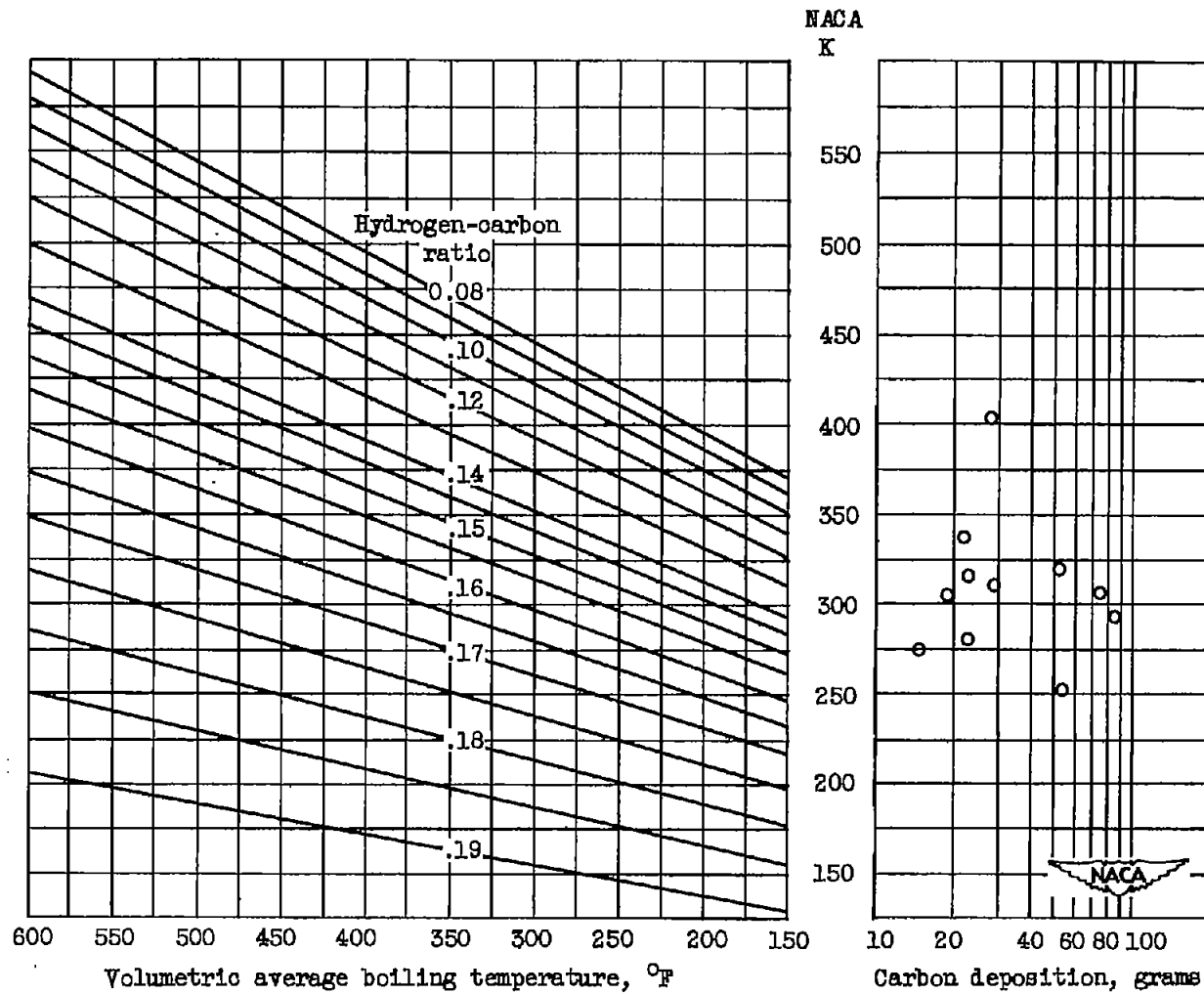
(c) J31 combustor (table II(d)).

Figure 4. - Continued. Correlation of carbon-deposition data with function of hydrogen-carbon ratio and volumetric average boiling temperature.



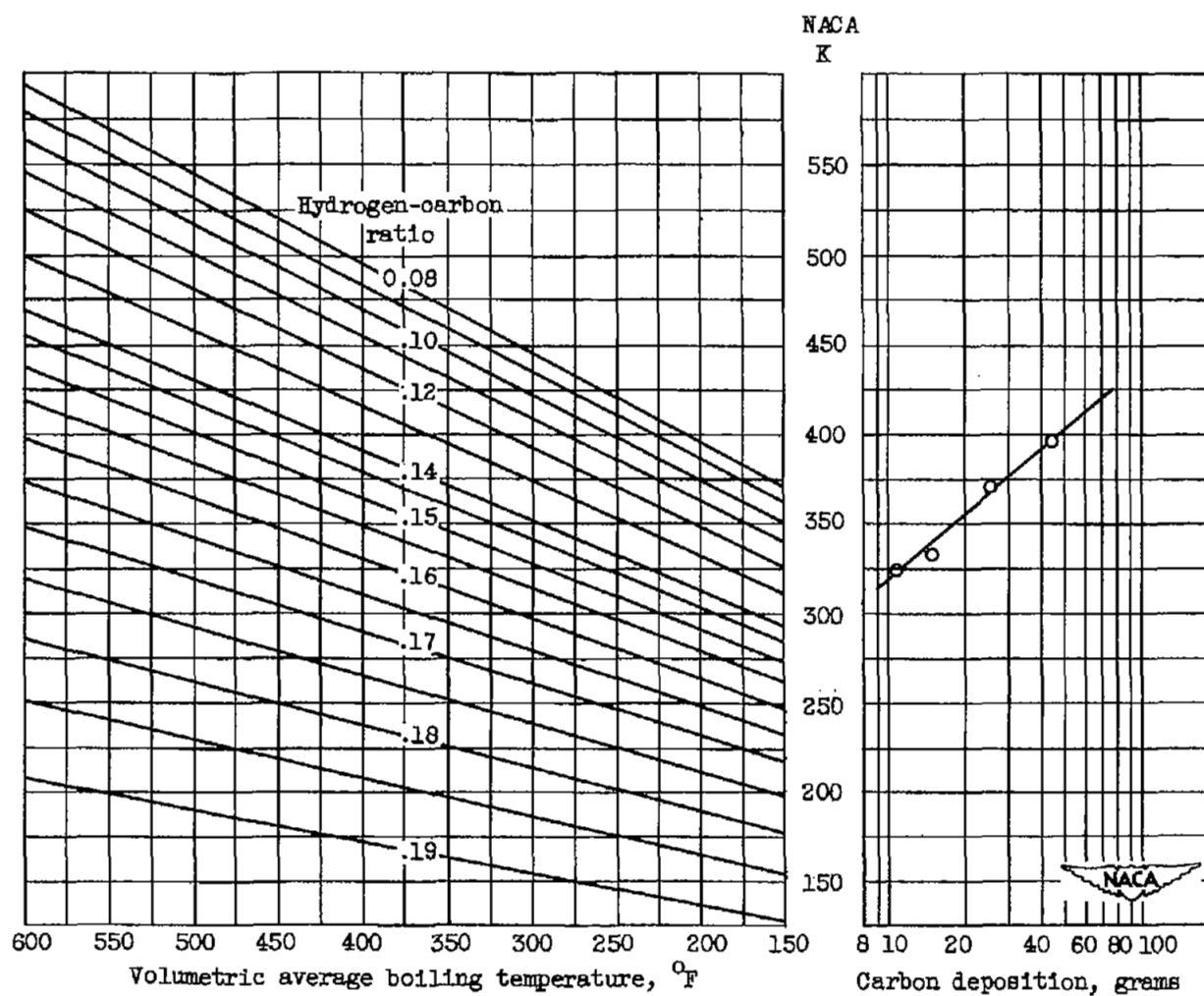
(d) J31 combustor (table II(f)).

Figure 4. - Continued. Correlation of carbon-deposition data with function of hydrogen-carbon ratio and volumetric average boiling temperature.



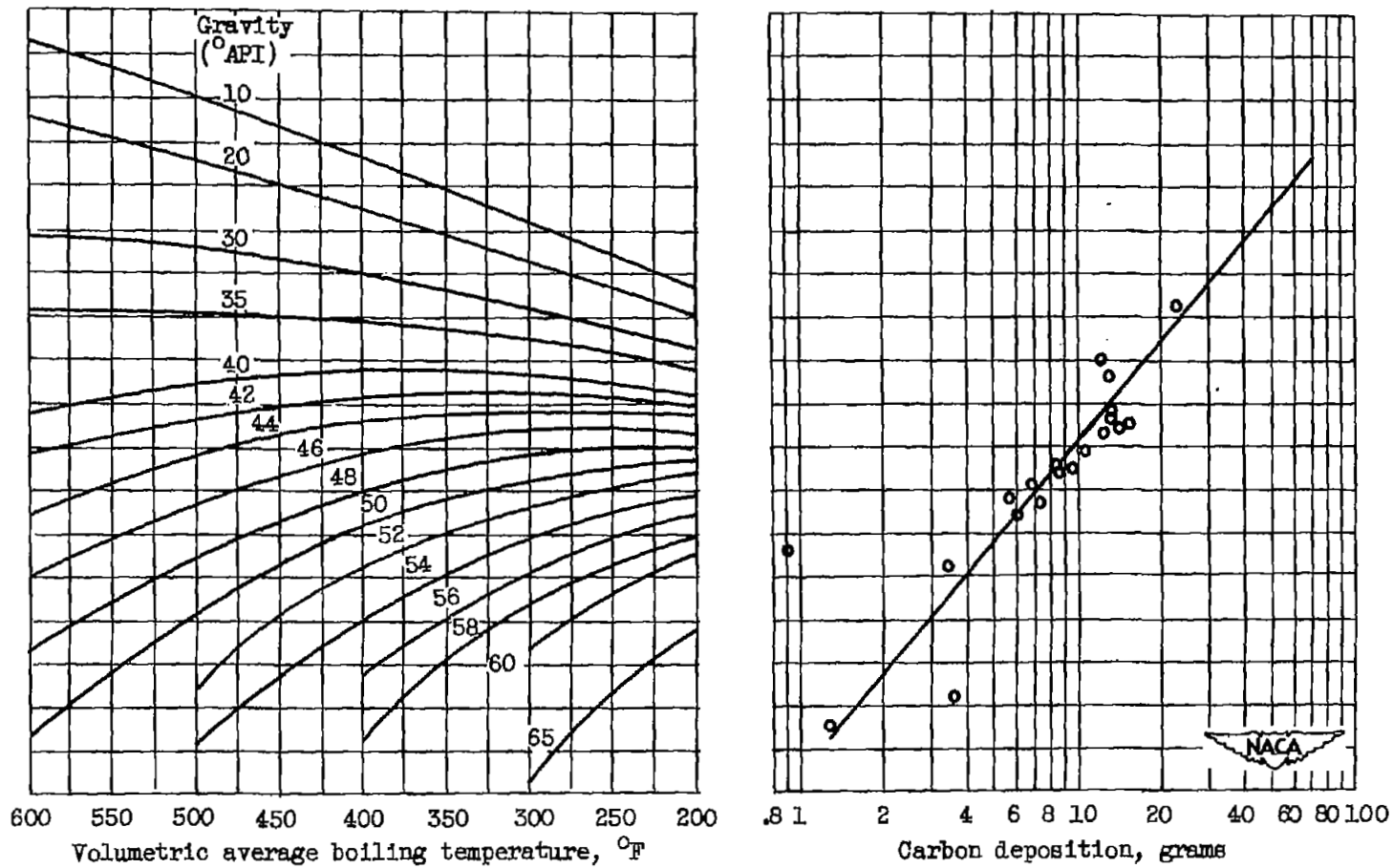
(e) J42 combustor (table II(h)).

Figure 4. - Continued. Correlation of carbon-deposition data with function of hydrogen-carbon ratio and volumetric average boiling temperature.



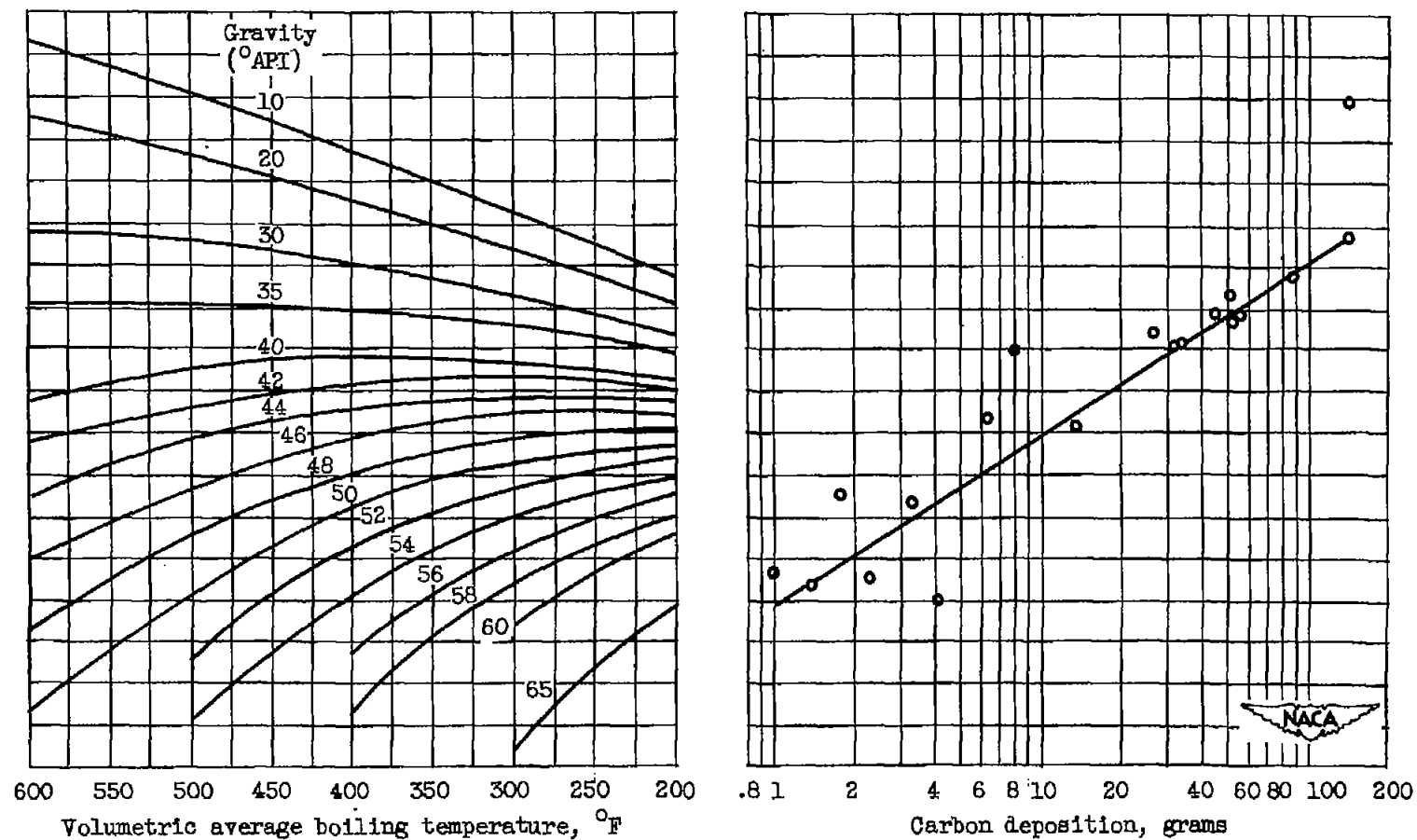
(f) J33 combustor (table II(1)).

Figure 4. - Concluded. Correlation of carbon-deposition data with function of hydrogen-carbon ratio and volumetric average boiling temperature.



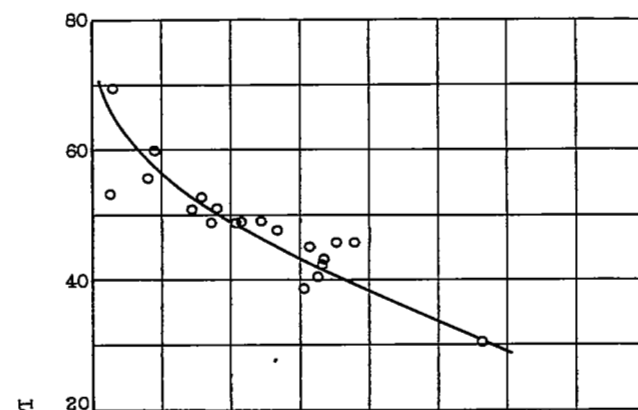
(a) J33 combustor.

Figure 5. - Correlation of NACA carbon-deposition data with function of gravity and volumetric average boiling temperature.

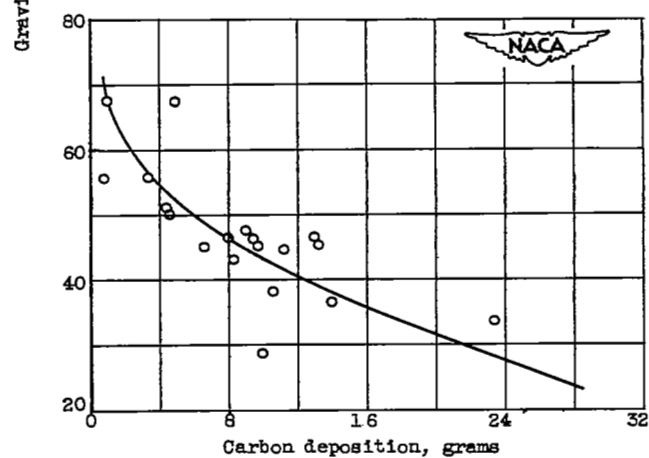


(b) Annular combustor.

Figure 5. - Concluded. Correlation of NACA carbon-deposition data with function of gravity and volumetric average boiling temperature.

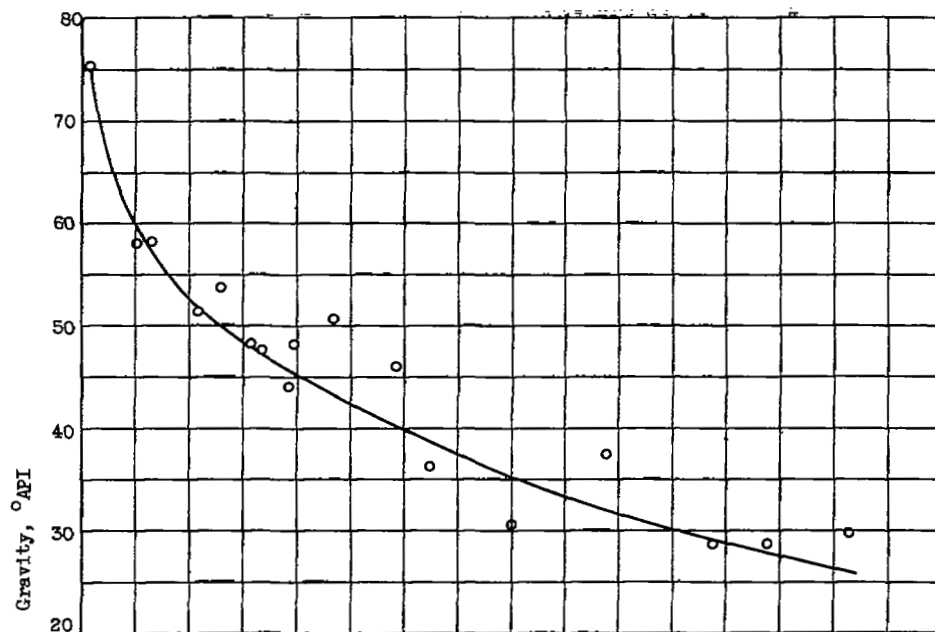


(a) J33 combustor (table I(a)).

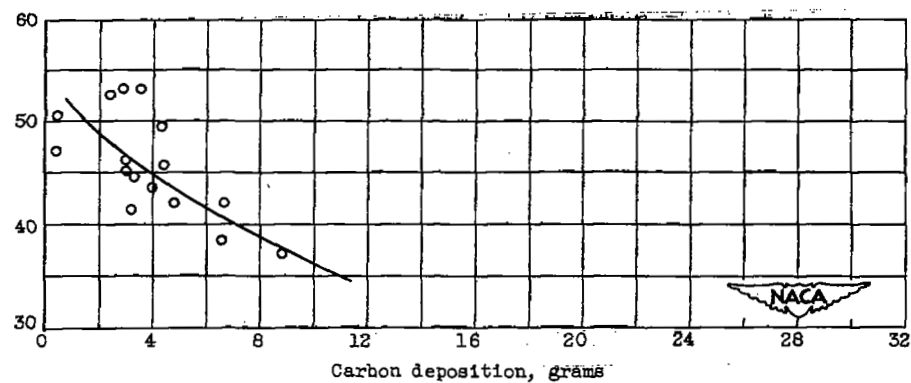


(b) J33 combustor (table II(b)).

Figure 6. - Correlation of carbon-deposition data with gravity.

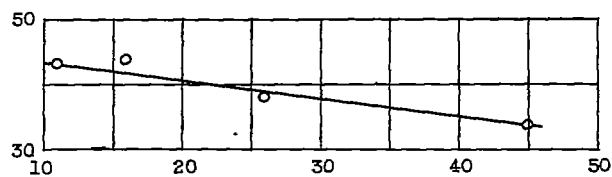


(c) J33 combustor (table II(e)).

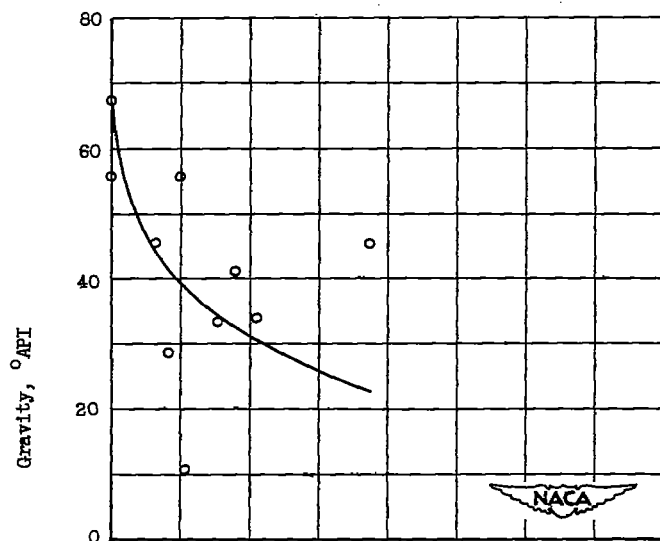


(d) J33 combustor (table II(g)).

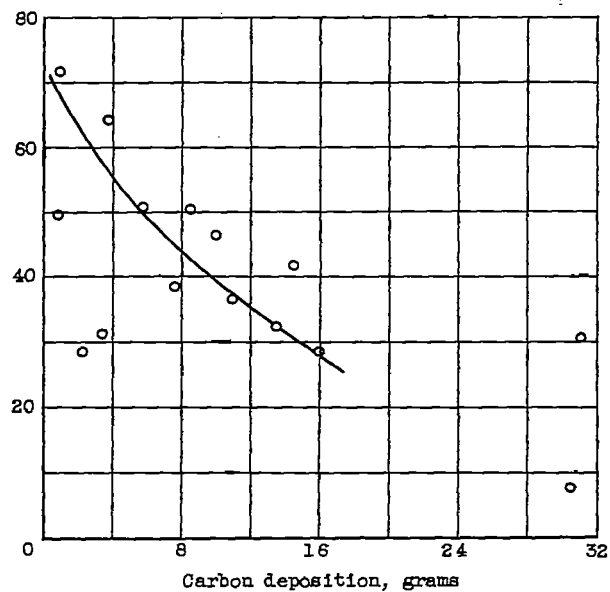
Figure 6. - Continued. Correlation of carbon-deposition data with gravity.



(e) J33 combustor (table II(i)).



(f) J31 combustor (table II(a)).



(g) J31 combustor (table II(f)).

Figure 6. - Continued. Correlation of carbon-deposition data with gravity.

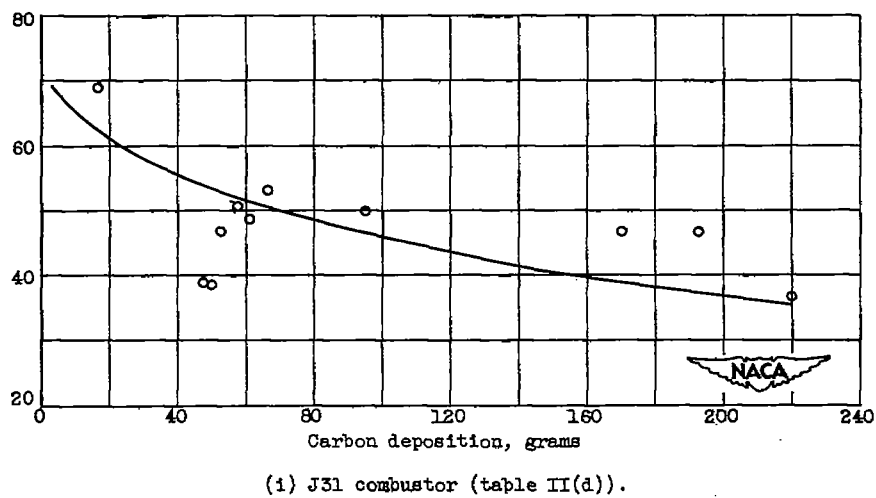
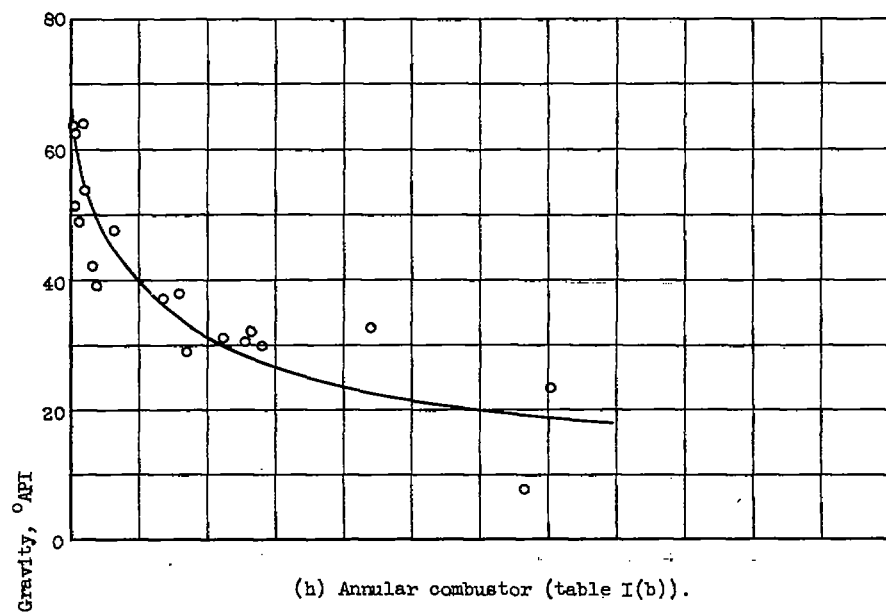


Figure 6. - Concluded. Correlation of carbon-deposition data with gravity.

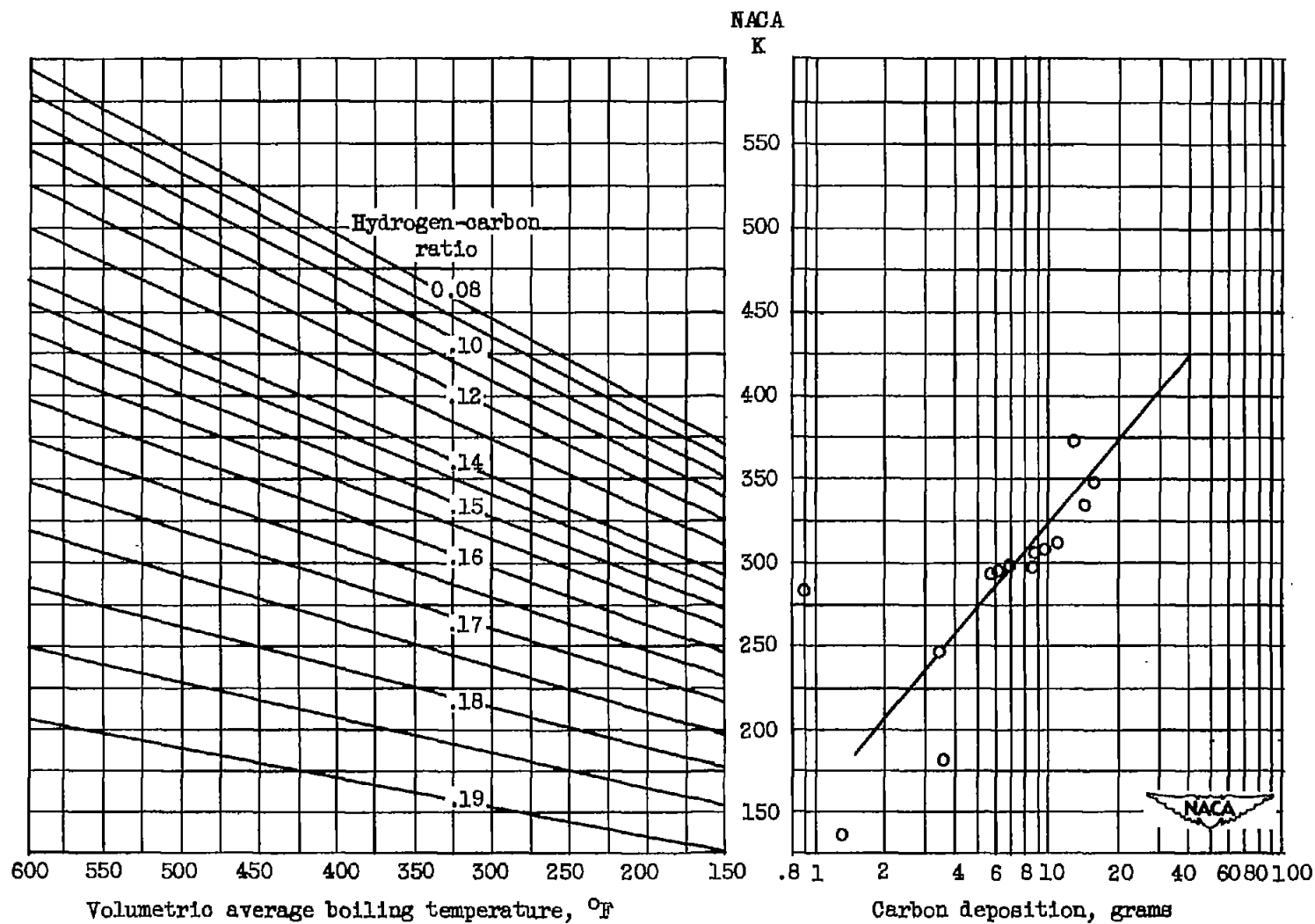


Figure 7. - Correlation of NACA carbon-deposition data (J33) with function of hydrogen-carbon ratio estimated from Linden correlation of volumetric average boiling temperature, gravity, and aniline point (reference 9) and volumetric average boiling temperature.

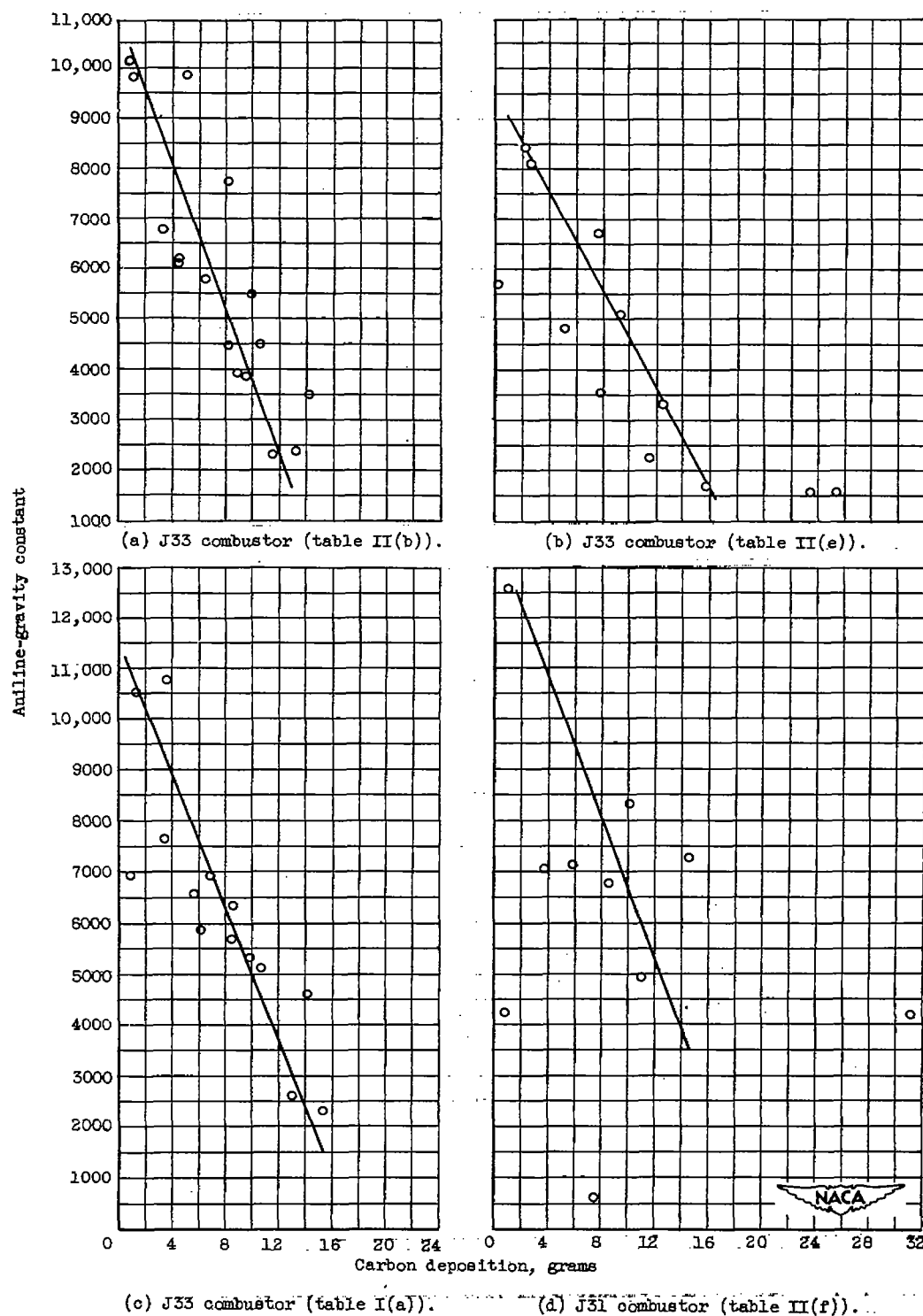
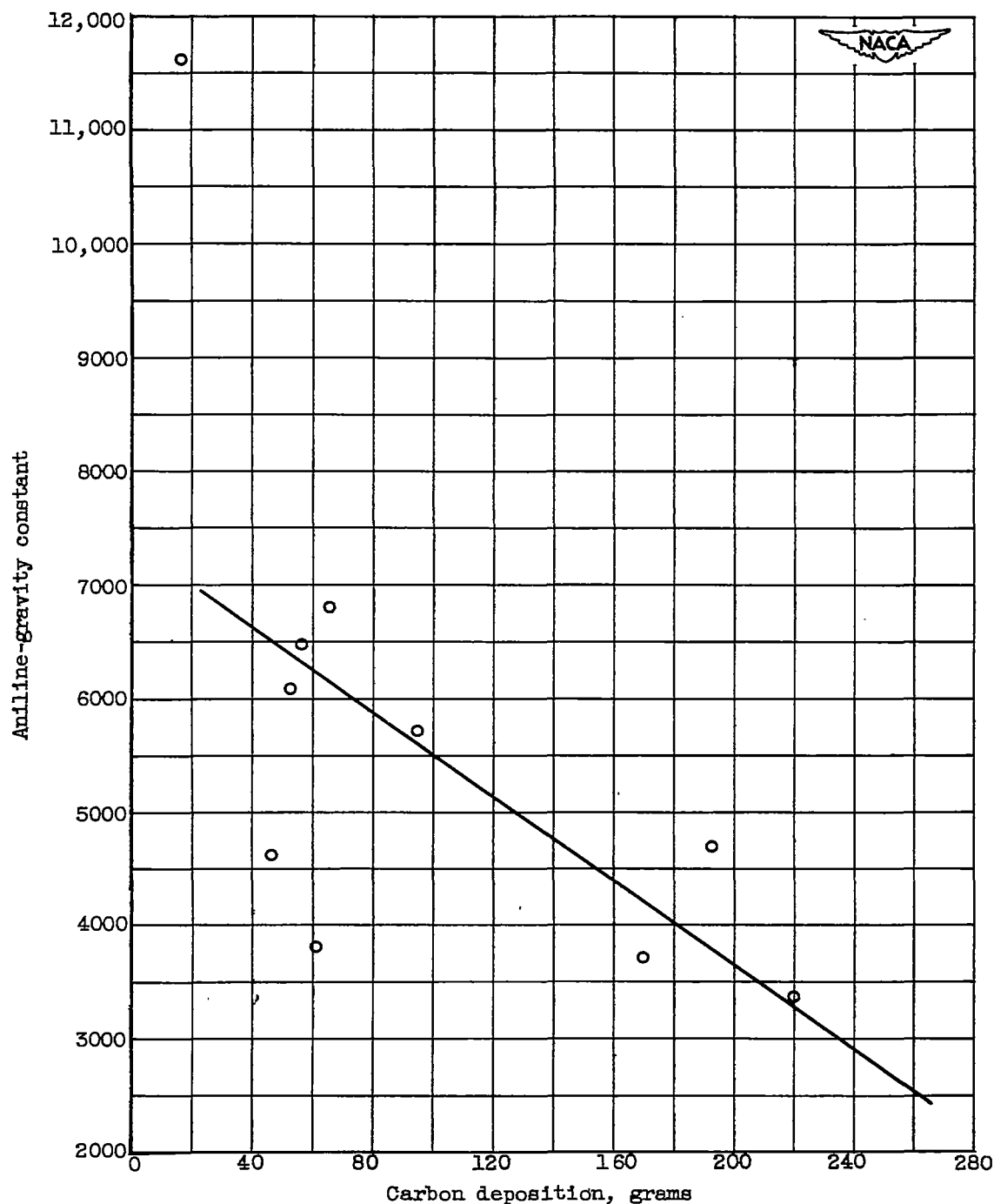
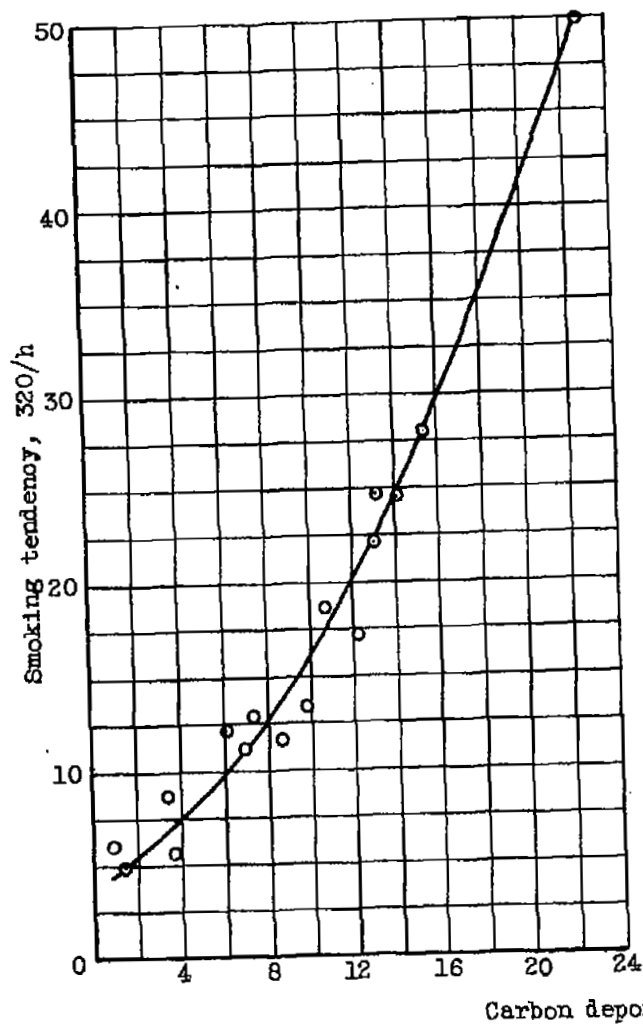


Figure 8. - Correlation of carbon-deposition data with aniline-gravity constant.

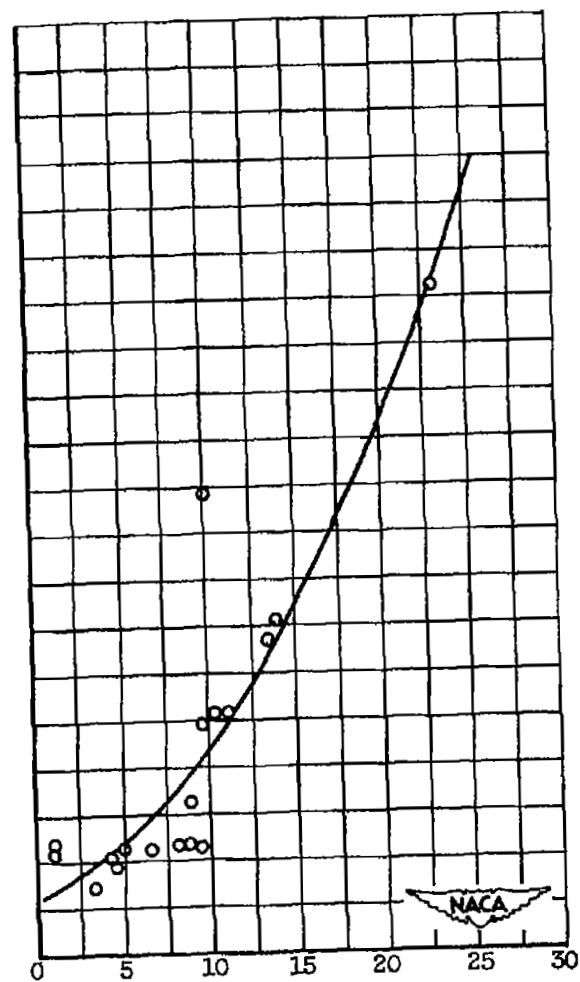


(e) J31 combustor (table II(d)).

Figure 8. - Concluded. Correlation of carbon-deposition data with aniline-gravity constant.

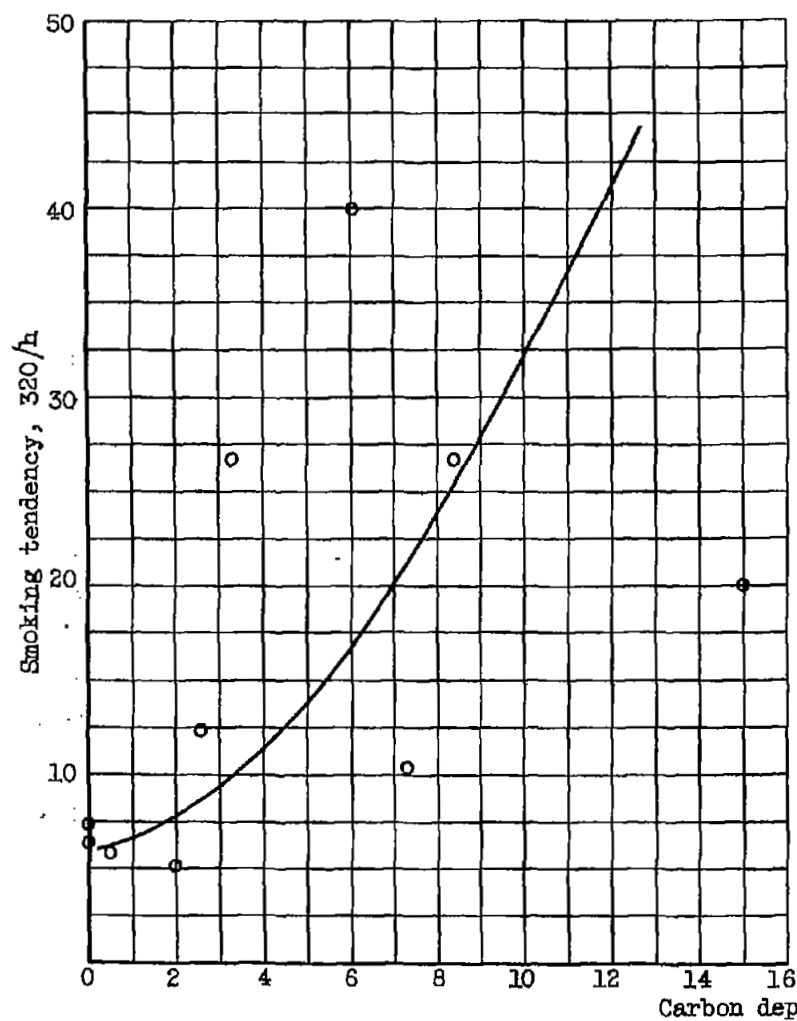


(a) J33 combustor (table I(a)).

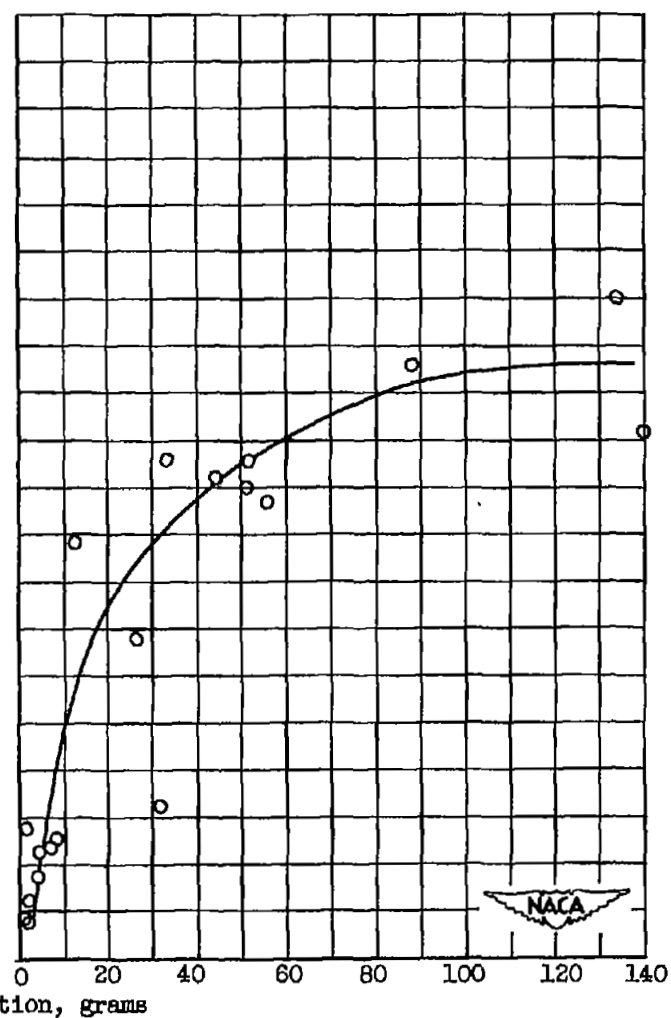


(b) J33 combustor (table II(b)).

Figure 9. - Correlation of carbon-deposition data with smoking tendency.

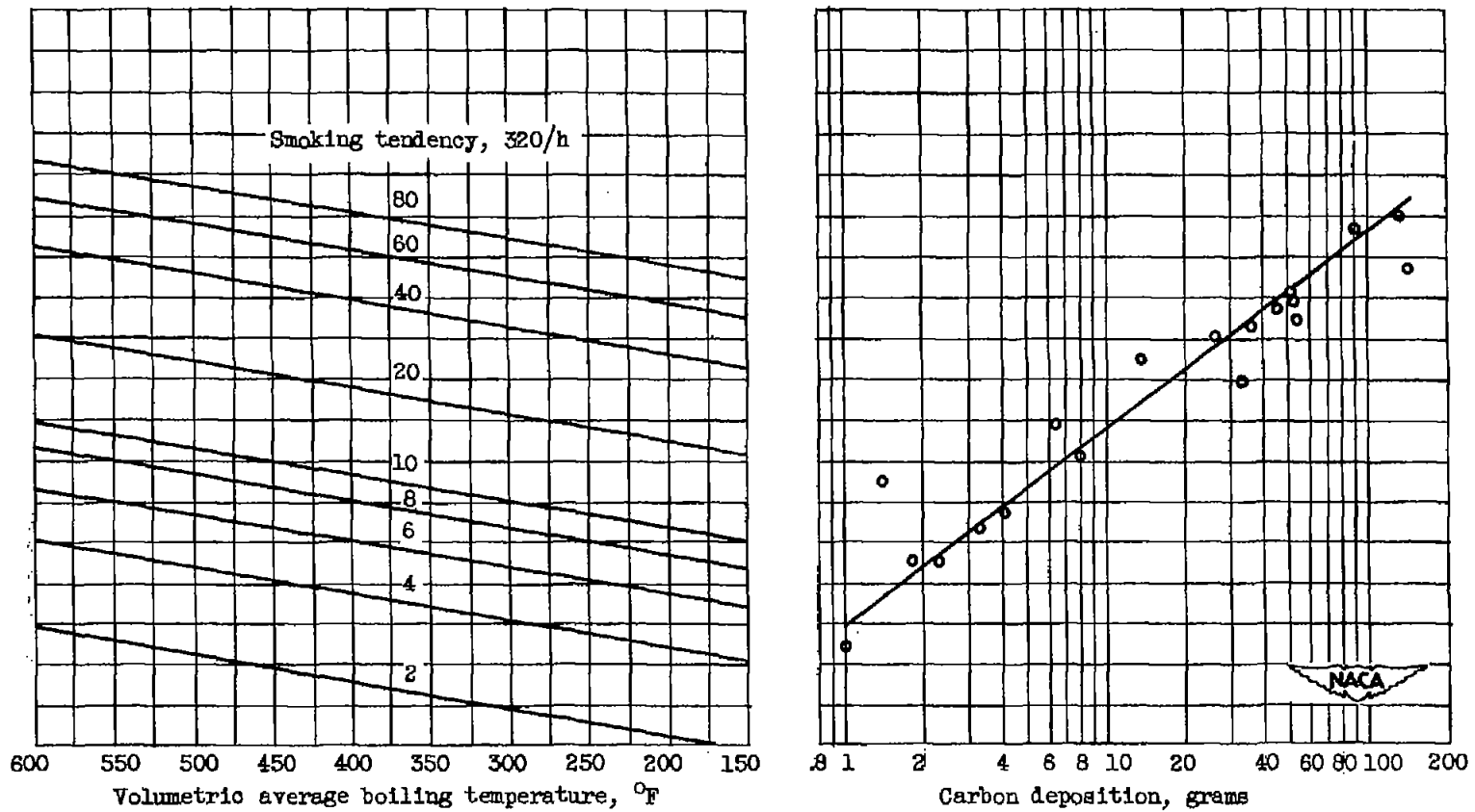


(c) J31 combustor (table II(a)).



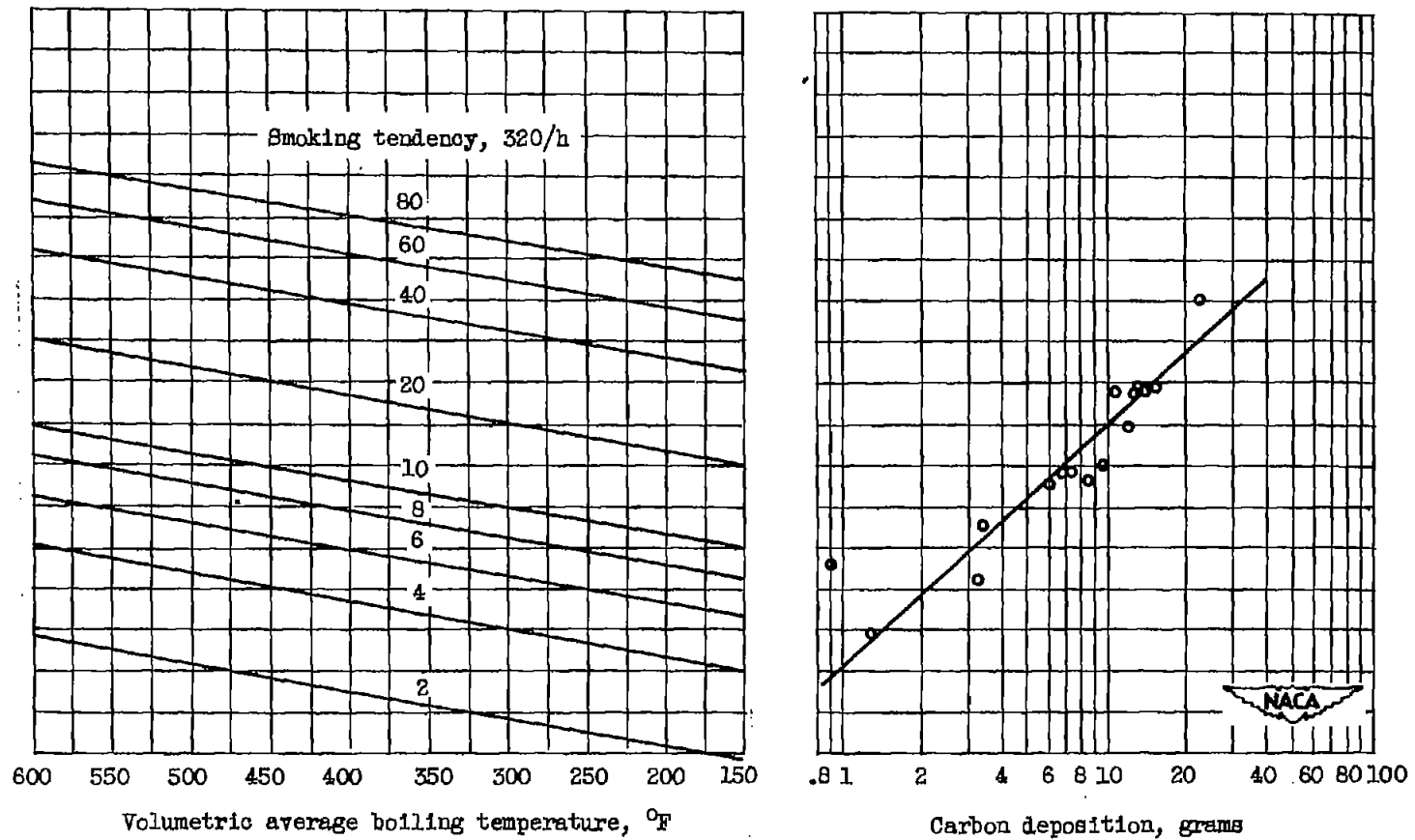
(d) Annular combustor (table I(b)).

Figure 9. - Concluded. Correlation of carbon-deposition data with smoking tendency.



(a) Annular combustor.

Figure 10. - Correlation of NACA carbon-deposition data with function of smoking tendency and volumetric average boiling temperature.



(b) J33 combustor.

Figure 10. - Concluded. Correlation of NACA carbon-deposition data with function of smoking tendency and volumetric average boiling temperature.

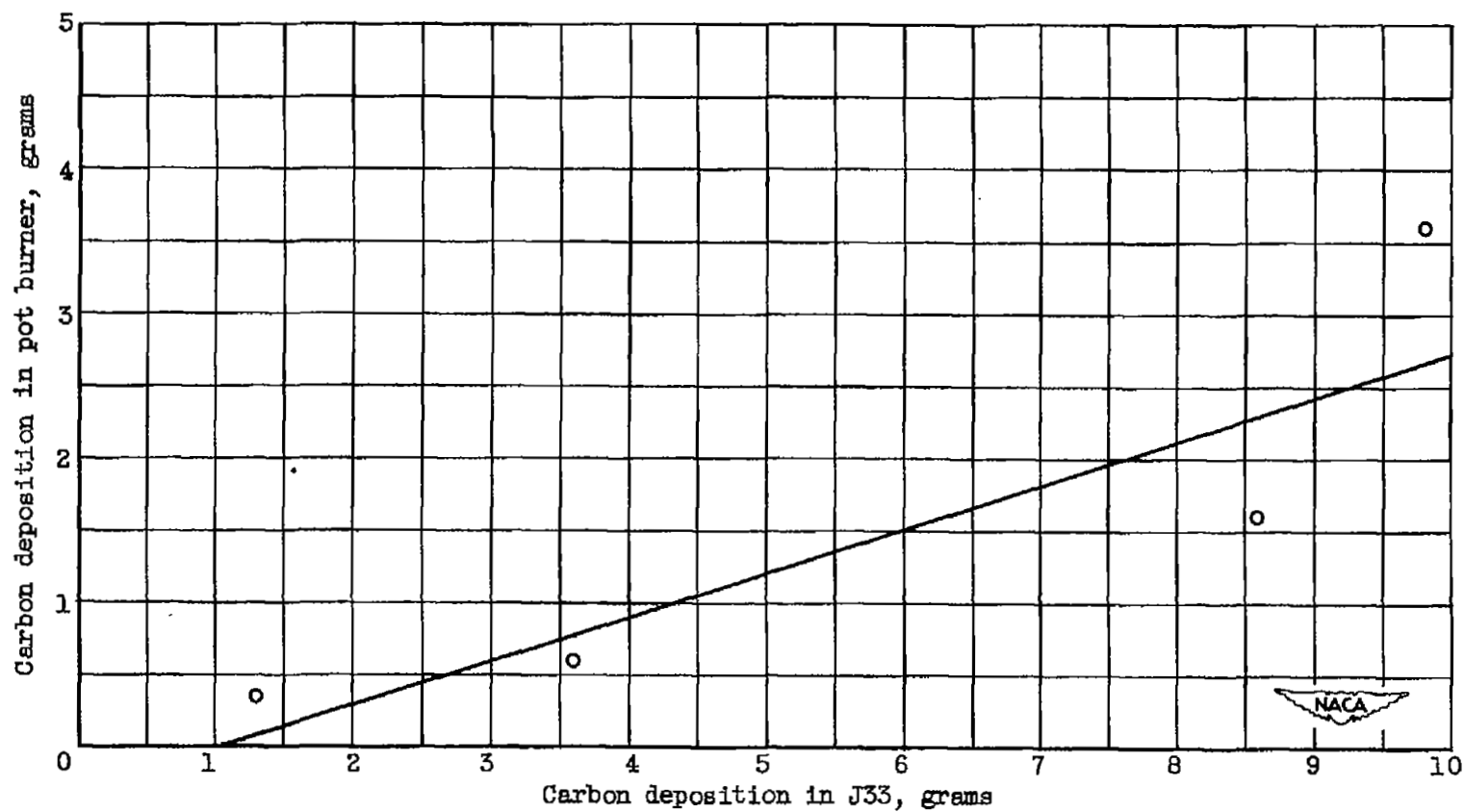


Figure 11. - Correlation of NACA J33 carbon-deposition data with 5-inch pot burner carbon-deposition data (unpublished).

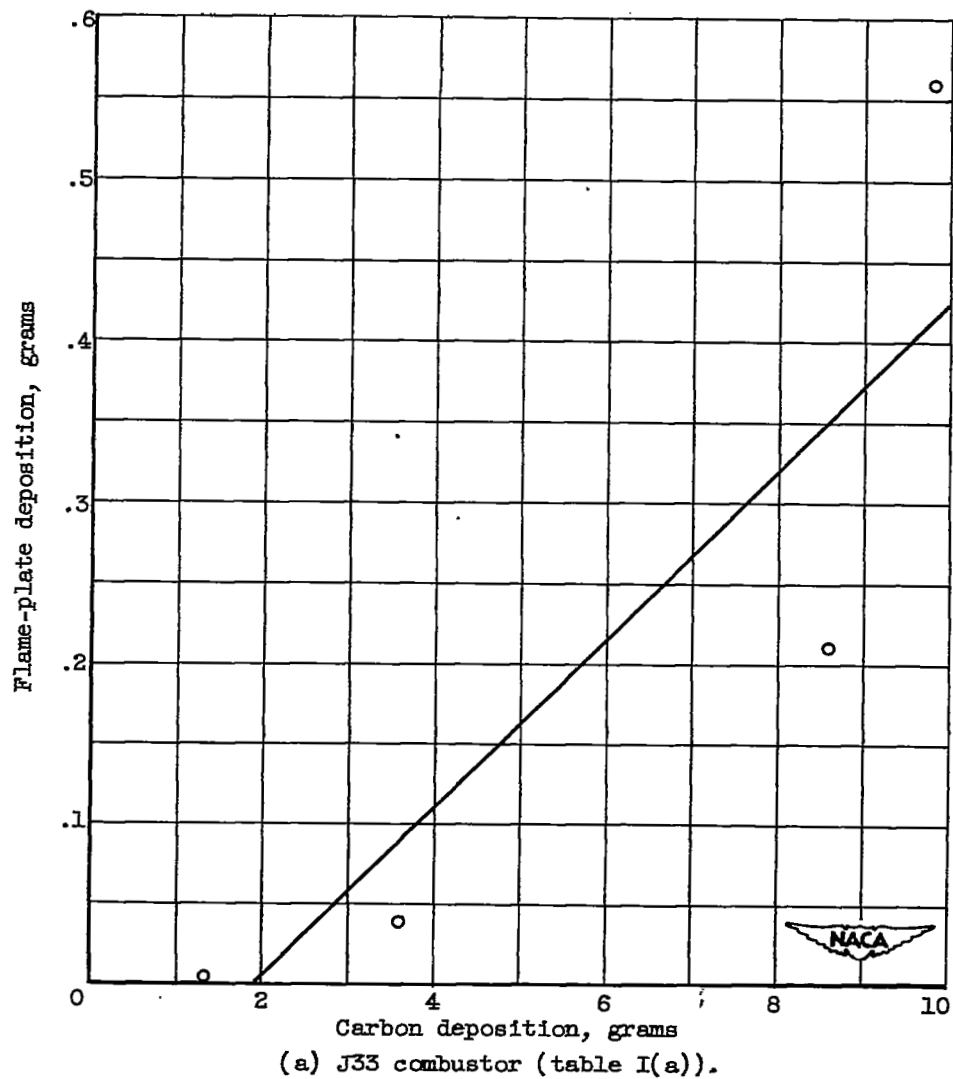
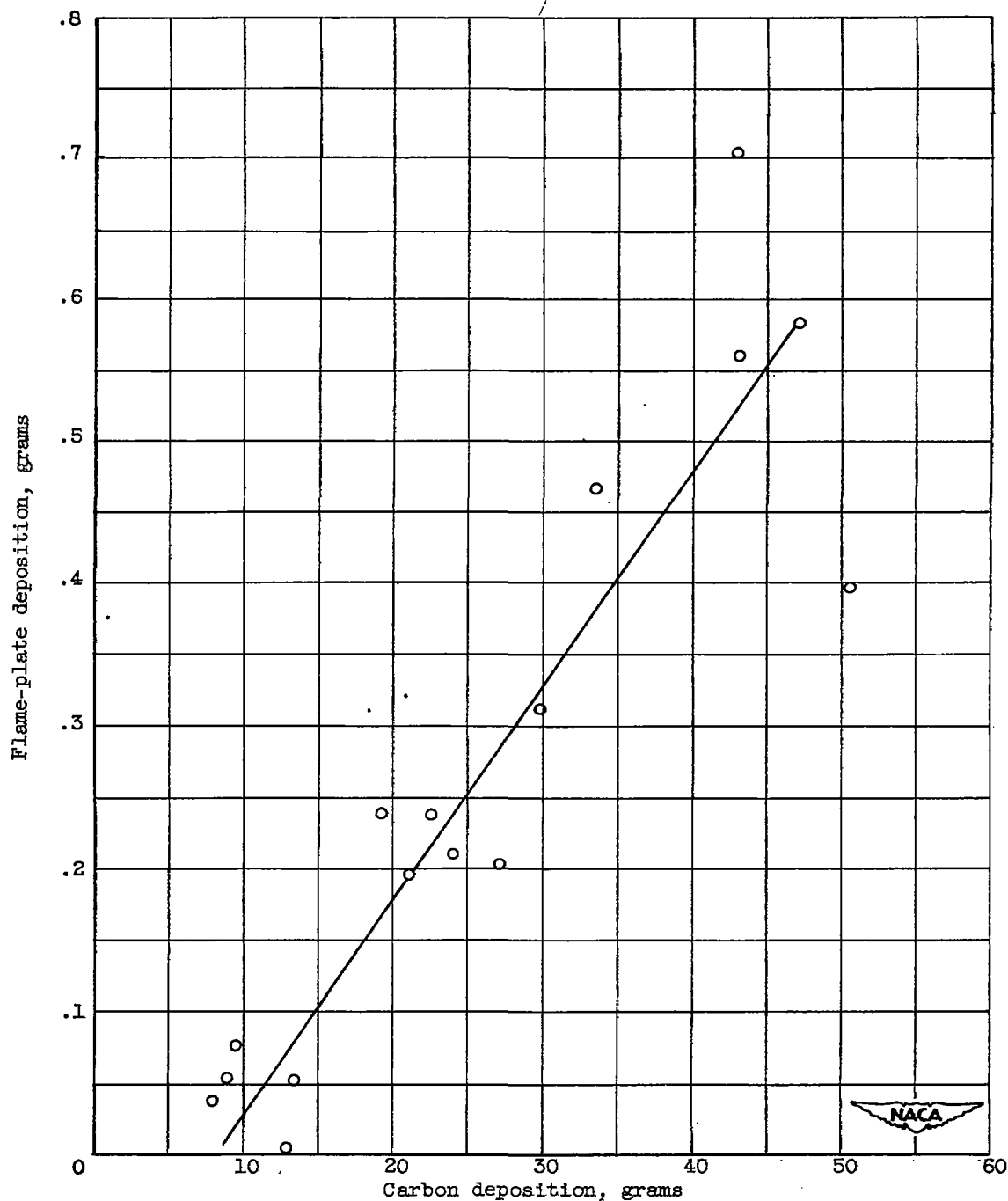
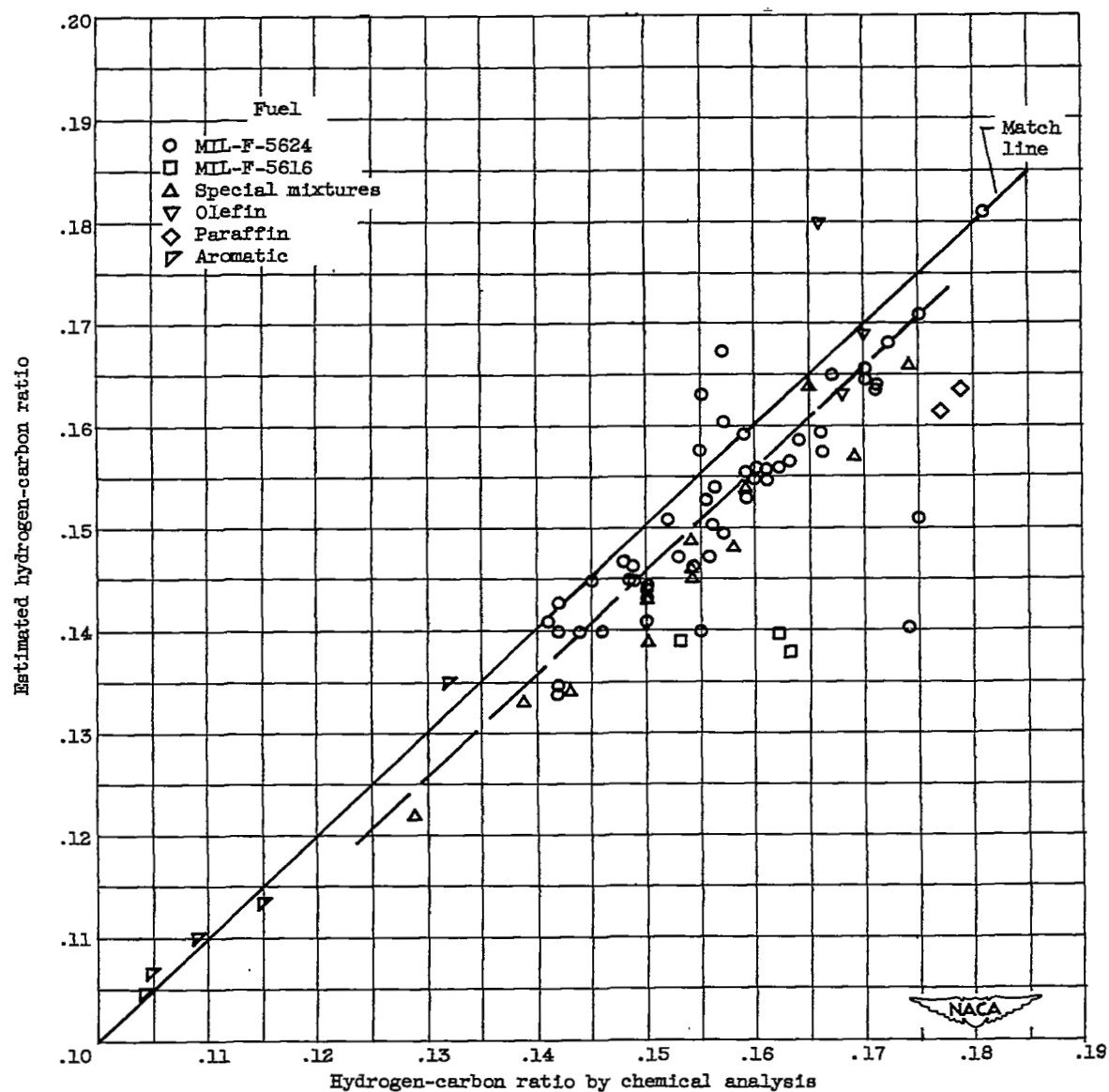


Figure 12. - Correlation of carbon-deposition data with flame-plate deposition data (unpublished).



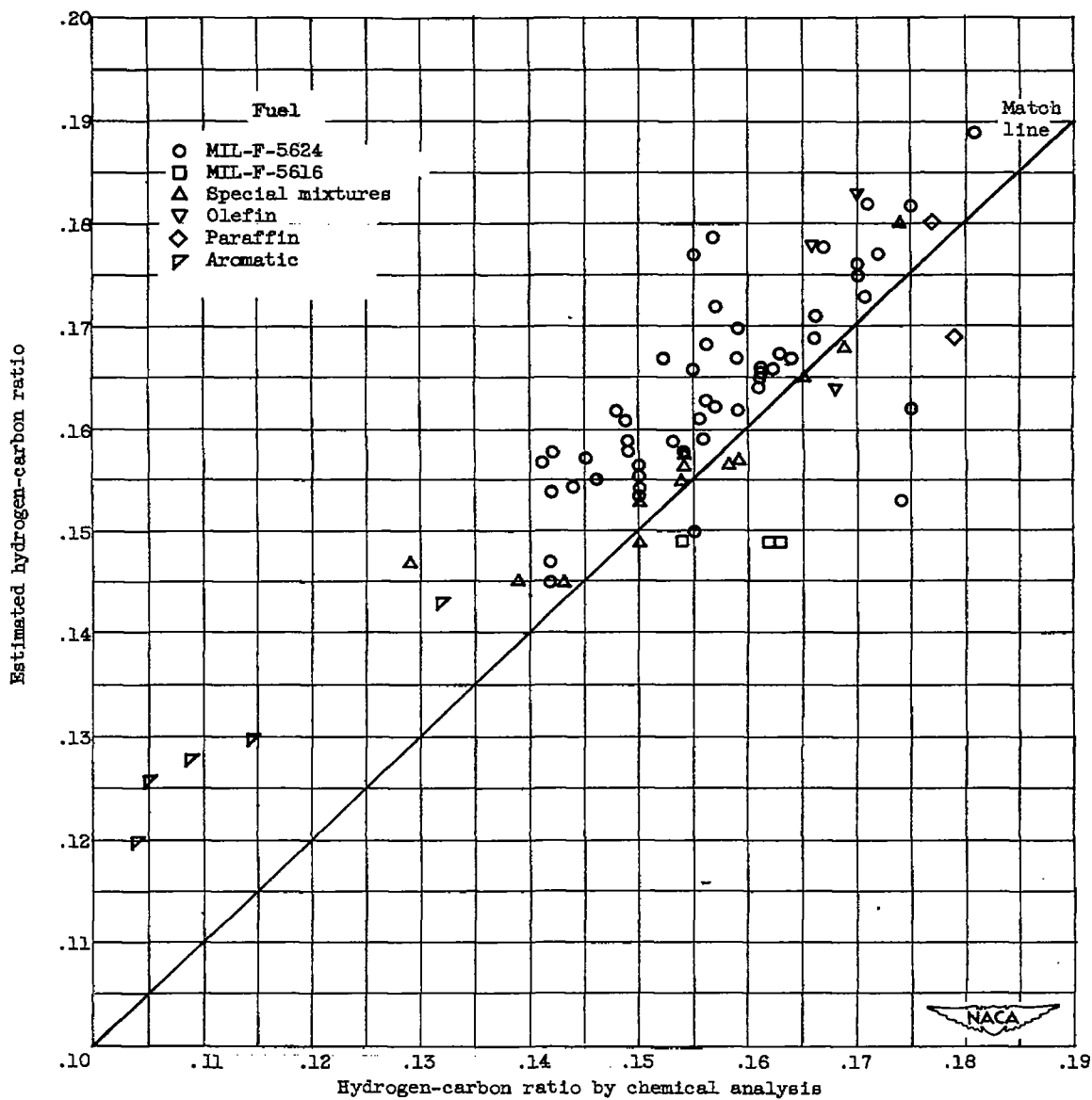
(b) Tubular combustor (unpublished data).

Figure 12. - Concluded. Correlation of carbon-deposition data with flame-plate deposition data (unpublished).



(a) Watson correlation of mean average boiling temperature and gravity (reference 8).

Figure 13. - Comparison of hydrogen-carbon ratios of fuels determined from chemical analysis with those estimated from two correlation methods.



(b) Linden correlation of mean average boiling temperature and gravity (reference 9).

Figure 13. - Concluded. Comparison of hydrogen-carbon ratios of fuels determined from chemical analysis with those estimated from two correlation methods.

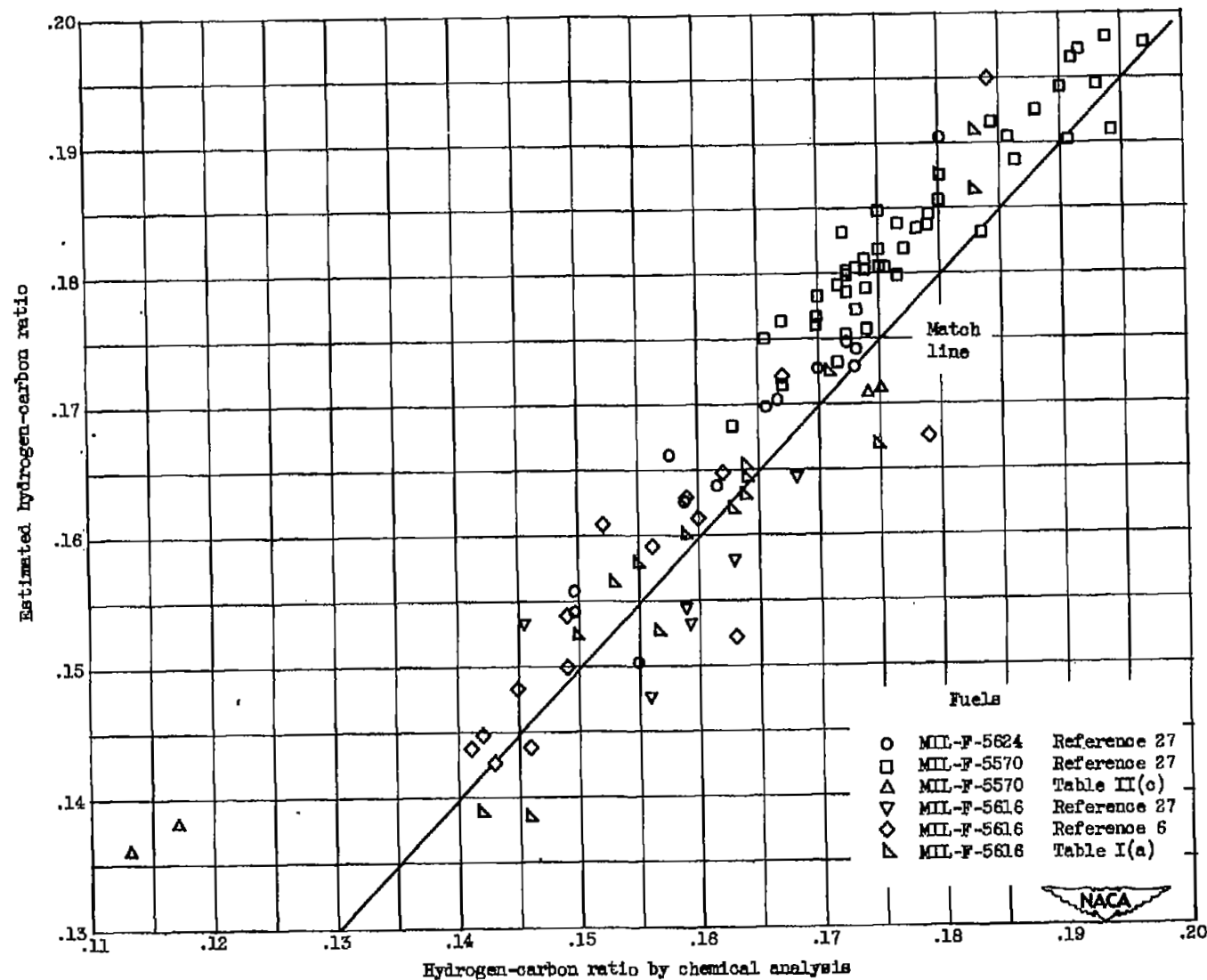


Figure 14. - Comparison of hydrogen-carbon ratios of fuels determined from chemical analysis with those estimated from the Linden correlation using volumetric average boiling temperature, gravity, and aniline point (reference 9).

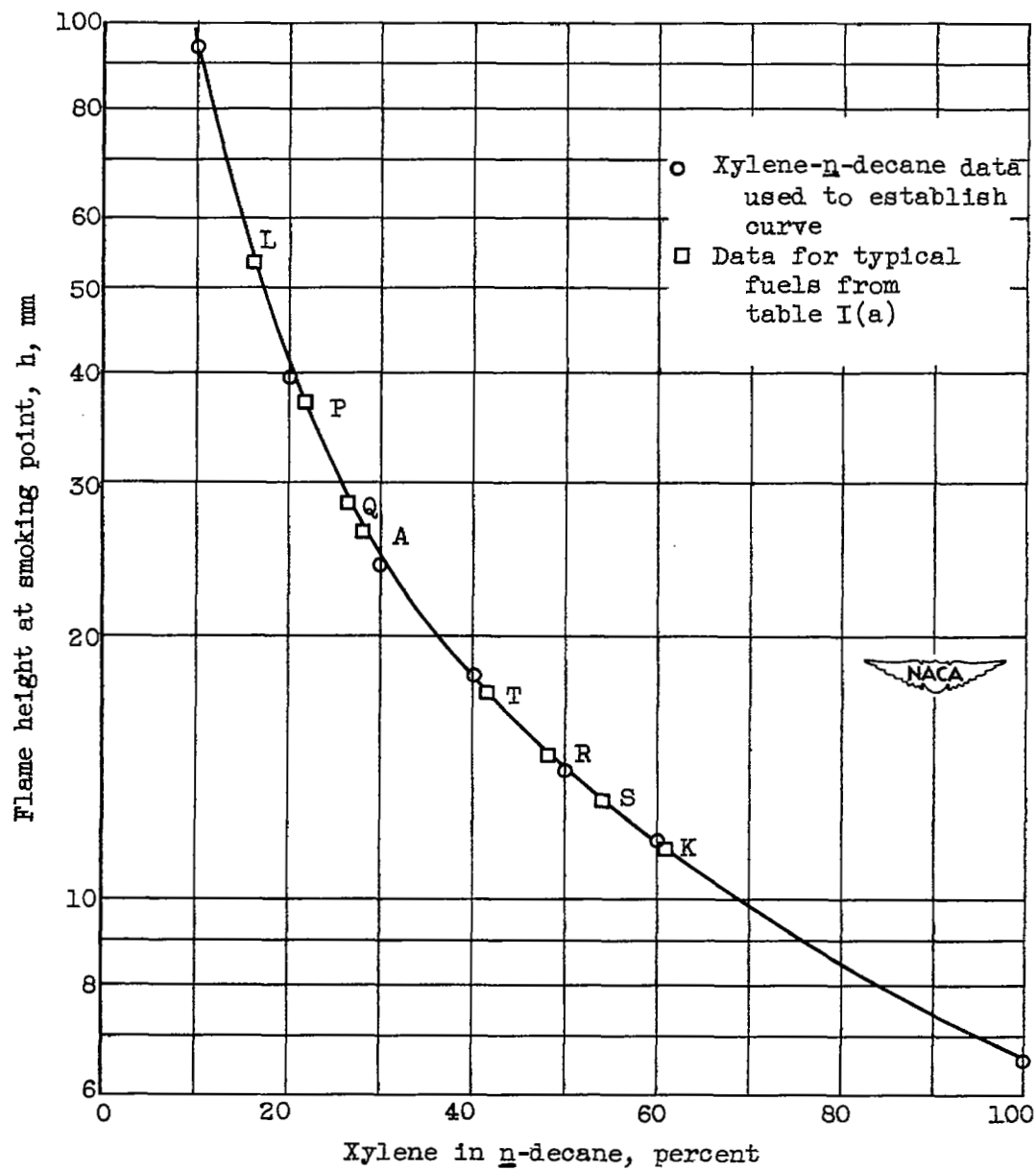


Figure 15. - Fuel blending curve of smoke-lamp flame heights.

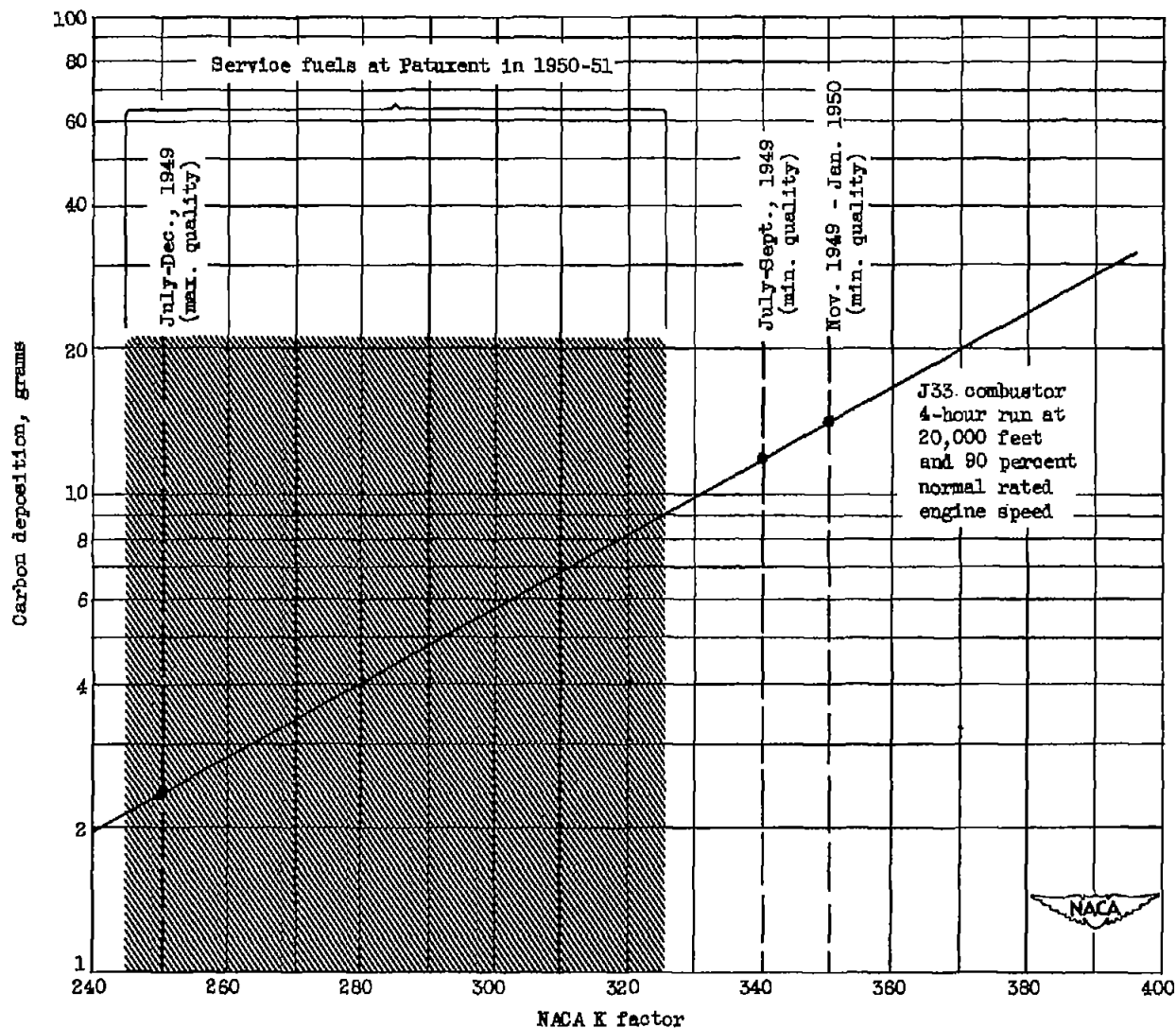


Figure 16. - Range of NACA K factor of fuels used at Naval Air Test Center, Patuxent River, Maryland.